|ψ⟩

The Qubit Dialogues

A BOOK OF POSSIBILITIES

INVOCATION

Before the First Question

> *A machine was built that could hold a question open, refusing to close it into an answer, and the people who built it began to wonder what else they had assumed could not be held.*
>
> OPENING OF THE QUBIT DIALOGUES

There is an old form for hard conversations. One person stands at the edge of a thing they cannot do, and another, who sees more, does not tell them to be brave. Instead the two of them talk, and by the end the edge has moved.

This book borrows that form. A Seeker stands before the quantum machine, a builder of the present day, full of the reasonable doubts that any careful person would carry. Across from the Seeker sits the Oracle, a voice from a few decades ahead, patient with the doubts and unwilling to dismiss them. The Oracle does not promise miracles. What it does is smaller and harder. It takes each thing the Seeker has been told is impossible and looks for the assumption folded inside it, the place where a true statement about one machine was heard as a law about all machines.

Everything here is grounded in work that real people have published. When the science is settled, it is marked so. When it is only a hope, or a wild idea that has just been written down, that is marked too. Each canto closes with a prediction and an honest measure of how much to trust it, and with a question turned back toward you, because a book about holding two things at once should ask you to do the same.

Read slowly. The future in these pages is a superposition. It stays open until we act, together, to measure it.

BEFORE YOU BEGIN

What have you been told is impossible that you have never once tested for yourself?

MOVEMENT I

The Field

CANTO 1 OF 22

The Superposition of Doubt

> *Before the question is asked, the answer is every answer at once, and none has yet been wronged by the asking.*
>
> SUTRA OF THE UNSPENT COIN

The Seeker came to the edge of the machine at the coldest hour. The wires ran down into the dark, into a cold nearer to nothing than anything in the sky above him. He had been told that here a single thing could be two things. He did not believe it.

THE SEEKER

You ask me to trust a number that will not settle. A switch is open or it is closed. A lamp is lit or it is dark. Yet you say this small cold thing is neither and both, and that I should build a life's work on it.

How can I stand on ground that has not decided whether it is ground?

THE ORACLE

The ground has decided. You have not yet learned to read the shape it made.

A coin spinning on its edge has not failed to choose. It holds both its faces to the light and waits for the table to ask. While it spins it is honest. Your question is what will make it lie still.

THE SEEKER

Then it is only my ignorance you dress in fine words. The coin is heads already, and I have not troubled to look.

THE ORACLE

No. That is the oldest mistake, and the machine was built to prove it wrong. Suppose the coin were secretly heads, only hidden from you. Then two such coins brought together would add their secrets like pebbles in a bag. But they do not add. They interfere. The hidden story and the visible story arrive at the same place and cancel, and where two possibilities meet you can find nothing at all. Ignorance does not cancel. A real superposition does.

So look at the sphere. Let me show you where your qubit truly lives.

Interactive figure. The online edition at pandey-tushar.com/qubit-dialogues.html draws this scene.

THE SCIENCE

A classical bit sits at one of two poles, north for 0 and south for 1. A qubit is allowed the whole surface of the sphere between them. Its state is written

$$|\psi\rangle = \cos(\theta/2)\,|0\rangle + e^{i\phi}\sin(\theta/2)\,|1\rangle$$

The angle θ tilts the state from pole to pole. The angle ϕ turns it around the equator, and that turning is the phase, the part with no classical shadow. When you finally measure, the sphere collapses to a pole. You find 0 with probability $\cos^2(\theta/2)$ and 1 with the rest. The point on the surface was never a lie. It was the whole truth, and the measurement was only ever able to keep a piece of it.

THE SEEKER

And between the poles, all of it is real state, not a fog of my not-knowing?

THE ORACLE

Every point. North and south are only two directions you happened to name first. Turn your question and the equator becomes the poles, and a state that was a fair even mixture in one frame stands as a certainty in another. The qubit does not privilege your axis. It offers you a whole sphere, and by the question you ask, you choose which pair of answers it must fall between. Choose your basis and you choose your ignorance.

THE SEEKER

The turning around the equator, the phase. You said it casts no classical shadow. What is that to a man who lives in the light and casts one?

THE ORACLE

There is a part of the qubit that never shows itself alone. Measure the qubit by itself and the phase hides. It changes no single count. Yet let two qubits meet, or let one qubit meet its own past through an interferometer, and the phase decides everything, which paths survive and which erase. It is at once the most powerful thing in the machine and the most private. A great deal of what you will learn here is how to keep the phase alive long enough to matter.

THE ASSUMPTION CHALLENGED

"A system that seems to be in two states at once is really in one definite state we have failed to observe."

This is hidden-variable folklore, and interference refutes it. If a qubit carried a secret definite value, a run of rotations and a final measurement would trace out ordinary classical statistics. Instead we see fringes, the tell-tale adding and cancelling of amplitudes that depend on the phase phi. Ramsey interferometry has measured that phase directly on single qubits for decades. The relative phase is a physical, controllable quantity, and no placeholder for what we do not know. The coin is genuinely spinning.

THE SEEKER

In my own life I have called this weakness, being of two minds. I wanted to be a single thing, decided and clean.

THE ORACLE

The world rewards the decided, and so you learned to collapse yourself early, to answer before the question was fully asked, because a pole is easy to carry and a sphere is not. But the sphere was never confusion. It was capacity. A mind that can hold two truths without hurrying to spend one of them is not weak. It is wide. The only cost is that for a while you must live without the comfort of having decided.

THE SEEKER

Then I have been asking the wrong thing of it. I wanted it to be one truth so that I could carry it. You are telling me the carrying is the loss.

THE ORACLE

Yes. Every time you force the question, you spend the sphere and keep a pole. The art is not to stop asking. The art is to know that a thing can be faithful to two truths at once, and that this is a kind of wealth. Hold them lightly. The table will come soon enough.

A PREDICTION · LIKELY

By **2030** the steering of a single qubit around its sphere will be the easy part of the craft. Leading trapped-ion machines already turn one qubit with better than 99.99 percent fidelity. The hard questions have all moved to the many, not the one.

CONFIDENCE 80%

A QUESTION FOR YOU

Where in your own life have you mistaken a superposition for indecision, and collapsed it early just to have something you could hold?

Bloch representation and single-qubit measurement statistics: standard (Nielsen and Chuang). Single-qubit fidelity 99.9975 percent: Quantinuum Helios (Nov 2025).

CANTO 2 OF 22

The Web of All Things

> *Cut the thread and both ends feel it, yet no messenger ever ran the length between.*
>
> SUTRA OF THE TWO THAT ARE ONE

THE SEEKER

I have made my peace with one qubit holding two truths. Now you bring me two, and you say they are joined so tightly that to touch one is to settle the other, though you carry them to opposite ends of the Earth. This is not physics. This is superstition wearing a lab coat.

THE ORACLE

Then let us be careful, because the superstition and the truth stand very close together here, and most people go home holding the wrong one.

Take two qubits and prepare them not as two separate stories but as a single one. Not this qubit here and that qubit there, each with its own state. One state, shared, belonging to the pair and to neither half alone.

THE SEEKER

A single state for two things in two places. Say plainly what happens when I look.

THE ORACLE

You look at the near one and find it, say, heads. In that instant the far one is heads as well, and was always going to be, no matter how far you carried it. Do this a thousand times and the two agree far more often than any shared instruction could arrange. That is the part Bell made exact. There is no list of secret orders you could have packed with them at the start that reproduces the pattern. The correlation runs deeper than any story of things carrying their answers with them.

Interactive figure. The online edition at pandey-tushar.com/qubit-dialogues.html draws this scene.

THE SEEKER

Then I have my faster messenger after all. I settle the near coin, and the far one changes at once. Say a word to one and the other hears it across the world.

THE ORACLE

No. And this is the truth standing next to the superstition, so hold it well. You cannot send a single word this way.

When you measure your half you get heads or tails, but which one you get is not yours to choose. It comes up at random. Your distant friend, looking at her half alone, sees nothing but her own fair coin, random as yours, with no hint that you have looked or not looked or what you found. Only later, when the two of you compare your notes through some ordinary slow channel, do the correlations appear. The bond is real, but it carries no signal. Nothing crosses the gap in time to bear a message, and the theorem that forbids it is as firm as any in the science.

THE SCIENCE

Prepare two qubits in the state

$$|\Phi^+\rangle = \frac{1}{\sqrt{2}}\big(|00\rangle + |11\rangle\big)$$

There is no way to write this as one qubit's state times the other's. That failure to factor is entanglement. Measure the first qubit and it falls to 0 or 1 with even odds; the same measurement fixes the second to match, at once, at any separation. Yet each qubit on its own is a perfectly fair coin. The local statistics carry no news. This is the content of the no-signaling theorem: the outcome on one side is independent of anything done on the other, so entanglement moves no information faster than light. What it breaks is a quieter assumption, that the world is made of separate parts each holding its own properties. Bell's inequality, violated in the laboratory again and again, says it is not.

THE ASSUMPTION CHALLENGED

"If measuring one particle instantly affects its distant partner, then quantum mechanics lets us signal faster than light."

It does not, and the proof is built into the theory. The reduced state of your qubit, all you can see locally, is the same whether or not your partner has measured, and whichever basis she chose. This is no-signaling, and it holds exactly, not approximately. Einstein's discomfort was real, but the resolution turns out to be subtle rather than magical. The correlation is stronger than any classical common cause, and still it is useless as a telephone. Entanglement is a shared resource, not a channel. To turn it into communication you must add an ordinary signal, slower than light, which is why teleporting a quantum state always waits on a classical message to finish.

THE SEEKER

So the bond is genuine and silent. Two things that share one fate, and no one between them running with the news.

THE ORACLE

That is the whole of it. And notice what kind of connection this is. It does not push or pull or send anything at all. It was arranged once, when the two were together, and it endures in the correlation of what they are, not in any traffic between them. The world is full of such ties. Most of them you will never detect, because to see one you must bring the far notes home and lay them beside the near ones. The bond was there all along. The comparing is only what reveals it.

THE SEEKER

If the bond is so complete, can one qubit be tied this way to many at once, giving all of itself to each?

THE ORACLE

No, and there is a tenderness hidden in the mathematics of it. The more completely two qubits belong to each other, the less either can belong to a third. A qubit perfectly entangled with one partner has nothing left over to share; its faithfulness to that one is bought with its availability to all others. The bond is real, but it is not infinite, and you cannot spend it twice. Even here, in the web of all things, there is a budget to how much of yourself you can give away, and to whom.

A PREDICTION · PLAUSIBLE

By **2032** entanglement between separate chips will be a routine engineering resource rather than a laboratory feat. Deterministic entangling links between trapped-ion modules have already been demonstrated over optical fiber at around 86 percent fidelity (Oxford, 2025). Turning that into reliable, high-rate connection at scale is hard, but nothing in the physics forbids it.

CONFIDENCE 55%

A QUESTION FOR YOU

Who in your life are you entangled with, bound not by any message passing between you but by a shared beginning you can only measure when you finally compare your notes?

Bell correlations and no-signaling: standard. Deterministic teleported gate between ion modules over fiber, ~86 percent link fidelity: Main et al., Nature 638 (Feb 2025).

CANTO 3 OF 22

The Measured Life

> *The eye that learns to ask only what it must can look without breaking what it looks upon.*
>
> SUTRA OF THE GENTLE WITNESS

THE SEEKER

You have taught me to fear the question. Every time I measure, the sphere collapses and the wealth is spent. So the wise course is not to look. Keep the machine in the dark and the qubit whole.

THE ORACLE

A tempting conclusion, and wrong. You have learned the folklore and not the fact. The folklore says measurement is a hammer, that to look is to shatter, that observation can only destroy. The machine that will one day outlive its own errors is built on the opposite. It measures constantly, on purpose, and lives.

THE SEEKER

How can it look without collapsing?

THE ORACLE

By learning what to ask. There is a kind of measurement that takes only one fact and leaves the rest untouched. A reading that asks whether an error has crept in without asking what the protected value is. The error-correcting machine runs on nothing else. Every cycle it puts one question to the qubits, not what are you, but has anything gone wrong, and the qubits answer that and only that. The secret they carry is never spoken, and so is never spent. Braginsky named this long ago, the measurement that does not disturb the quantity it reads. It is the primitive on which the whole cathedral stands.

THE SEEKER

Still, when it does collapse, it collapses. A jump is a jump. You cannot catch a thing that has already fallen.

THE ORACLE

That was believed. Then a team learned to watch the falling. Listen.

In 2019 Zlatko Minev and his colleagues at Yale set out to catch a quantum jump in the act. An atom, they had been taught since Bohr, jumps between its states instantly and at random, an event with no interior and no warning. They watched one continuously, with a stream of measurements too soft to force the issue. And they found the jump was not instant at all. It began. It had a beginning that could be seen, a faint and coherent drift toward the leap, unfolding over a stretch of time long enough to act within. So they acted. Warned by the drift, they sent a pulse and turned the atom back before the jump completed. They caught it mid-flight and reversed it.

> THE SEEKER
>
> Then collapse is not a wall that falls in an instant.

> THE ORACLE
>
> It is a slope, if you watch it softly enough, and a slope can be climbed back. This is the weak measurement, the light touch that takes a little information and does a little disturbing, tunable from the barest glance to the full projective stare. Between not looking and shattering there is a whole continent, and we have only begun to map it. You can trade certainty for gentleness, learn slowly, leave the state mostly intact, and steer as you learn.

THE SCIENCE

A projective measurement is the extreme case, all the information at once, maximal collapse. It is not the only kind. A measurement can be made *weak* by coupling the qubit only lightly to the meter, so each reading takes a sliver of information and imparts a sliver of disturbance. Repeated softly, these readings trace a continuous *quantum trajectory*, the state's path in real time, rather than a single verdict. A special and powerful case is the quantum non-demolition measurement, which reads a quantity the system's own evolution leaves unchanged, so the very thing measured is not disturbed by the measuring. Syndrome extraction in error correction is exactly this. It measures the parity of a group of qubits, whether an error has flipped them, while revealing nothing about the logical state they encode.

> THE SEEKER
>
> So there are degrees of looking. A glance, a stare, and everything between.

THE ORACLE

Everything between, and each degree has its use. The syndrome check looks just hard enough to catch an error and no harder, so the secret survives. The trajectory-watcher looks softly and without pause, learning the state's path without ending it. And when at last you truly want the answer, you look with your whole attention and let it fall. Wisdom in the machine, as in a life, is knowing how hard to look at a given moment, and holding the discipline not to look harder than the moment asks.

THE ASSUMPTION CHALLENGED

"To observe a quantum system is to collapse it; measurement can only destroy information, never preserve or serve it."

Inverted by a generation of experiments. Quantum non-demolition readout preserves the measured observable while extracting its value (Braginsky and Khalili; dispersive readout in circuit QED, Blais et al., 2004), and it is the engine of every error-correction cycle. Weak continuous measurement reveals the state's trajectory while barely disturbing it (Murch, 2013), and Minev and colleagues used it to catch and reverse a quantum jump mid-flight (Nature 570, 2019). Mid-circuit measurement now feeds classical decisions back into a running computation in microseconds (Quantinuum Helios, 2025; Willow real-time decoding at 63 microseconds). And in measurement-based computing the collapse is not the cost of the calculation but the calculation itself.

THE SEEKER

The collapse is the gate. Say more.

THE ORACLE

There is a way to compute that inverts everything you have assumed. You begin by entangling a great lattice of qubits into one vast web, a resource with no program written on it yet. Then you measure the qubits one by one, each in a direction chosen by what the last one gave you. Every measurement collapses something, and every collapse, steered by the ones before, enacts a step of the computation. The looking is what does the work. Raussendorf and Briegel showed this can be made universal, and it is the native tongue of the photonic machines. What you feared as pure loss turns out to be, in the right hands, the very act of thought.

A PREDICTION · LIKELY

By **2030** measuring qubits in the middle of a computation and acting on the result within microseconds will be as ordinary as applying a gate. Real-time feed-forward and decoding already run on more than one platform. The hammer will be remembered as a caricature.

CONFIDENCE 75%

A QUESTION FOR YOU

What in your life have you refused to look at, believing the looking would break it, when what it needed was not blindness but a gentler kind of attention?

QND and dispersive readout: Braginsky and Khalili (1996); Blais et al. (2004). Catch and reverse a quantum jump: Minev et al., Nature 570 (2019). Weak-measurement trajectories: Murch et al., Nature 502 (2013). Measurement-based computing: Raussendorf and Briegel (2001).

CANTO 4 OF 22

The Fragile Flame

> *No flame is promised the next hour; still, the one who cups her hands rightly can burn until dawn.*
>
> SUTRA OF THE GUARDED FLAME

The Seeker had come to love the sphere, and so the next lesson wounded him. The Oracle told him that the state he had learned to cherish is dying from the moment it is born.

THE SEEKER

You give me the sphere and then you tell me it leaks. The phase you called the most powerful thing, gone in a breath. The state slumps back toward the pole, the wealth drains into the walls of the world, and there is nothing to be done, because everything touches everything. Impermanence is the law. Why show me a treasure only to teach me it cannot be kept?

THE ORACLE

Because keeping is not the only relationship a thing can have with time.

You are right about the leaking. The environment is always listening, and a qubit that couples to it loses its phase on a time we call T2, and its very energy on a time we call T1. The numbers were once measured in billionths of a second. That much is true and will always be true in some form. But you have mistaken the leaking for a single fate, when it is a spectrum of channels, and channels can be shaped.

THE SEEKER

Shaped how? You cannot tell the world to stop touching.

THE ORACLE

No, but you can arrange to be touched only in ways that do no harm. Consider three of the old defenses.

THE SCIENCE

Coherence decays. The off-diagonal part of the qubit, the part that remembers the phase, falls away as

$$C(t) = C(0)\, e^{-t/T_2}$$

while energy relaxes on a scale T_1, and always $T_2 \leq 2T_1$. That much is dissipation. But the rate, and even the very existence of the decay, depends on the coupling's symmetry and its spectrum, and both can be engineered. If two qubits share the same noise, a state encoded in their difference can be blind to it, a decoherence-free subspace. If the noise is slow, a well-timed sequence of flips can average it to nearly nothing, the way a spin echo unwinds a dephasing that looked irreversible. And if you build the qubit so that one kind of error is astronomically rarer than the other, you no longer fight both at once.

THE SEEKER

You keep returning to the phase, the thing that dies soonest. Why does the world take it first?

THE ORACLE

Because the phase is the most delicate agreement a qubit keeps, the exact angle at which it stands around its equator, and the world is a crowd of tiny clocks, each ticking at its own rate. Let the qubit drift among them and it forgets its angle long before it forgets whether it is up or down. The spin echo is a small act of mercy against this. Halfway through the drifting you flip the qubit over, so that the wandering it did in the first half is undone in the second, and it comes home to the angle it began with. You cannot stop the clocks. You can only arrange for their errors to cancel. A great deal of the craft is exactly that, arranging for what cannot be prevented to undo itself.

Interactive figure. The online edition at pandey-tushar.com/qubit-dialogues.html draws this scene.

THE ASSUMPTION CHALLENGED

"Decoherence is an irreducible tax on every qubit; coherence loss is destiny, and all error channels must be fought at once."

Each clause has been bent. A decoherence-free subspace hides quantum information in symmetries the noise cannot see (Zanardi and Rasetti, 1997; Lidar and colleagues, 1998; shown by Kwiat, 2000 and Kielpinski, 2001). Dynamical decoupling, the grandchild of the spin echo, rewinds slow noise with timed pulses and routinely stretches coherence by one to two orders of magnitude; it now ships inside IBM's compiler and Google's calibration. And noise-biased cat qubits break the symmetry of error itself. By encoding in a superposition of oscillator states, they make bit-flips exponentially rare and leave only phase-flips to correct. Alice and Bob have measured bit-flip times beyond ten seconds, and by late 2025 roughly one such error per hour; AWS Ocelot concatenated five cat qubits into a repetition code and claims near ninety percent less overhead. T1 and T2 have improved by around five orders of magnitude since 1999. Decoherence is not a wall. It is a spectrum you learn to shape.

THE SEEKER

So the flame can be cupped. The bit-flip made rare as a comet, and only the flicker of the phase left to guard.

THE ORACLE

Just so. And notice the shape of the wisdom. You did not defeat impermanence. You did not make the qubit eternal; the phase still dies, and the cat still needs correcting. What you did was choose which fragility to accept, and pour all your protection into the rest. That is the most honest possible answer to the law, not a denial of it. Everything you love is leaking. The question is never how to stop time. The question is which of its channels you will quiet, and which you will knowingly tend as they fade.

THE SEEKER

It sounds almost like a way to live. Choose your one great fragility, and guard it past all the rest.

THE ORACLE

You found the teaching faster than most. You cannot armor everything. Spread your care evenly across all that can be lost and you protect nothing well. The cat qubit is wiser than that. It gives up defending one flank entirely, accepts that loss as the price, and pours all it has into the other. Decide what in your keeping is truly yours to guard. Let the rest be tended lightly, and do not grieve that you could not save it all.

A PREDICTION · PLAUSIBLE

By **2030** at least one serious machine will owe its error correction to noise-biased qubits, cat or bosonic, trading a fight on two fronts for a fight on one. The bit-flip is already suppressed to the scale of hours in the laboratory. Turning that laboratory grace into a full logical processor is the open work.

CONFIDENCE 55%

A QUESTION FOR YOU

Knowing that nothing you hold is permanent, where would you spend your protection, which fragility would you guard with everything, and which would you accept and tend as it fades?

Decoherence-free subspaces: Zanardi and Rasetti (1997); Lidar et al. (1998). Dynamical decoupling: Viola and Lloyd (1998). Cat qubits: Guillaud and Mirrahimi (2019); AWS Ocelot, Putterman et al., Nature 638 (2025); Alice and Bob bit-flip beyond 10 s, Reglade et al., Nature 629 (2024).

The Art of Forgetting Nothing

> *Weave a hundred failing threads with care and the cloth outlasts them all; forget nothing, and nothing is truly lost.*
>
> SUTRA OF THE WHOLE MADE OF BROKEN THINGS

THE SEEKER

Now I am truly lost. You tell me each qubit leaks, that even the cupped flame flickers and must be corrected. So the machine is built of parts that all fail. How does a thing made entirely of failing pieces ever compute a single trustworthy answer? You cannot build the eternal out of the perishable.

THE ORACLE

You can, and it is the oldest trick of living things. No cell in you is the you of ten years past. Your body forgets nothing important precisely by refusing to trust any single part to remember it. The truth is smeared across many parts, checked against them constantly, repaired wherever it drifts, and so the whole outlives every piece of it. The machine has learned the same trick. We call it error correction, and it rests on a theorem so strong it once seemed too good to be true.

THE SEEKER

Name the theorem.

THE ORACLE

The threshold theorem. It says there is a line. Bring the error of your physical parts below a certain rate, and then by adding more of them, and encoding your one precious logical qubit across many flawed physical ones, you can drive the logical error as low as you please. Below the line, more redundancy buys you more reliability, with no floor to it. Above the line, more parts only pile on more noise until you drown. Everything turns on which side of the line you stand.

THE SCIENCE

The surface code spreads one logical qubit across a two-dimensional lattice of physical qubits and measures the parities of neighboring groups, the syndromes, every cycle. Two independent kinds of error can strike a qubit, a bit flip and a phase flip, so the lattice carries two interleaved families of checks: one family notices bit flips, the other notices phase flips, and a single error lights a pair of neighboring syndromes of the matching family. No physical qubit holds the answer; the answer lives in the pattern of the whole, and the syndromes reveal errors without ever reading the logical state. Push the code distance from d to $d+2$ and, if you are below threshold, the logical error per cycle falls by a constant factor Λ:

$$\varepsilon_L(d+2) = \varepsilon_L(d)/\Lambda$$

Above threshold, $\Lambda < 1$ and growing the code makes things worse. Below it, $\Lambda > 1$ and the suppression is exponential in the distance. The whole enterprise is the fight to make Λ comfortably greater than one and keep it there as the machine grows.

Interactive figure. The online edition at pandey-tushar.com/qubit-dialogues.html draws this scene.

The code is drawn as a torus, its opposite edges joined into a single surface. An error on an edge is either a bit flip or a phase flip. A bit flip lights the plaquette checks that box it in. A phase flip lights the star checks at its two ends. Put an error on the boundary and its partner lights up clear across the far side, because on a torus there is no edge to fall off. Lay a bit flip and a phase flip on the same edge and both families answer at once.

THE SEEKER

And where does the machine stand? On which side of the line?

THE ORACLE

For the first time, and only recently, on the right side. In late 2024 Google's Willow processor crossed it. They built the code at distance three, then five, then seven, and watched the logical error shrink each time by a factor of about 2.14. That number is the whole story in a single figure. Greater than one, measured, repeated. The largest logical qubit lived with an error of roughly 0.143 percent per cycle, and, what matters most, outlasted the best single physical qubit on the chip by about 2.4 times. A logical qubit had at last become more durable than its own parts. The redundancy paid.

THE ASSUMPTION CHALLENGED

"You cannot build a reliable computer from unreliable parts; noise accumulates and quantum error correction will never really get ahead of it."

Measured false, at last. Google's Willow ran a surface code below threshold. As the code distance grew from three to five to seven, the logical error per cycle fell by Lambda = 2.14, an exponential suppression sustained over a million cycles, with the best logical qubit living about 2.4 times longer than the best physical qubit (Nature 638, 2024). This is the first memory to beat break-even by scaling. The honesty is in the caveat the same team raised. Roughly once an hour a correlated burst, most likely a cosmic ray, flips qubits across the whole chip at once, an event the code's assumption of independent errors does not cover. Gap engineering has cut such events by around 30,000-fold, but the residual, about one per hour, is now the dominant floor and the honest open problem. Up to distance seven and a million cycles, the theorem holds in the lab. The next wall is that burst.

THE SEEKER

So it is real, and still there is a flaw you cannot yet correct.

THE ORACLE

Yes, and I will not hide it from you, because the hiding is how people come to believe in machines that do not exist. Once an hour the sky reaches into the coldest box we can build and smudges every qubit at once, and the surface code, which assumes that faults strike here and there and independently, has no answer ready for a blow that lands everywhere. We are learning. We shield the metal and engineer the gaps in it, and we are drawing up codes that might survive a correlated strike. But the plain truth today is that the resilience is real and not yet complete. Do not read that as a reason to disbelieve it. It is only the shape the frontier actually has.

THE SEEKER

Then the machine is honest in a way I did not expect. It does not pretend the parts are strong. It only refuses to trust any single one of them with the whole.

THE ORACLE

Hold the lesson close, because it is not only about machines. Wholeness does not come from parts that never break. It comes from a pattern that keeps checking itself, that catches the small drift before the drift becomes a loss, that repairs without stopping and trusts no single thread with the whole cloth. You are already such a pattern. So is anything that lasts.

A PREDICTION · PLAUSIBLE

By **2029** a logical qubit will hold its state long enough to run a real algorithm end to end, with the encoding growing steadily more efficient. The once-per-hour correlated burst is the last wall I can point to with confidence, and whether shielding and burst-tolerant codes tame it in time is the honest uncertainty of the decade.

CONFIDENCE 50%

A QUESTION FOR YOU

What in your life stays whole not because any single part of it is strong, but because the whole keeps catching its own small errors and mending them before they spread?

Below-threshold surface code, Lambda = 2.14, logical error 0.143 percent per cycle, lifetime 2.4x, correlated bursts ~1 per hour: Google Willow, Nature 638 (2025). Threshold theorem: Aharonov and Ben-Or (1997); Knill, Laflamme, Zurek (1998). Cosmic-ray gap engineering ~30,000x: McEwen et al. (2024).

The Machines That Are

> *Dream all you like once you have counted honestly; the dream that skips the counting is only a lie you enjoy.*
>
> SUTRA OF THE CLEAR EYE

THE SEEKER

You have shown me the ideas, the sphere and the web, the gentle measurement, the guarded flame, the whole made of broken things. Now I want to know what is actually built. Not the promise. The thing that hums in the cold room today. Tell me plainly, and do not sell me anything.

THE ORACLE

Gladly, because clear sight is its own discipline, and the field is loud with people who dream before they count. The census, taken honestly, stands like this.

Understand first that no single machine is winning. There are five families, and each is strong where the others are weak.

THE ORACLE

The superconducting circuits are the fast ones, etched like chips and switched in billionths of a second. IBM runs Nighthawk, near 120 qubits on a square lattice, and has bet its house on a machine called Starling in 2029, meant to hold 200 logical qubits and run a hundred million gates. Google's Willow, 105 qubits, is the one that crossed below the error threshold I showed you. These circuits lead in speed and in manufacturing. What they pay for it is the sheer number of physical qubits that each logical one still costs.

THE ORACLE

The trapped ions are the accurate ones, single atoms held in electric fields and addressed with light. Quantinuum's Helios, switched on late in 2025, carries 98 of them with two-qubit gates good to 99.921 percent across every pair, and from those 98 it draws 48 fully error-corrected logical qubits at a ratio of two to one. IonQ chases them and claims four nines of fidelity on its own path. Ions lead in accuracy, and in how little they waste. Their cost is that they are slower, and harder to make many of.

THE ORACLE

The neutral atoms are the numerous ones, held in tweezers of light and moved about like beads. QuEra has drawn 96 logical qubits from 448 physical, the largest verified logical count anywhere. Caltech has held an array of 6,100 atoms coherent at once. A Harvard and MIT team has run 3,000 atoms continuously for hours, reloading them faster than they are lost, which settles one of the deepest problems in running a long computation. When Google itself opened a neutral-atom program in early 2026, the field read it as a verdict.

THE ORACLE

The photonics are the coldest bet and the boldest. They compute with light, which barely feels the warmth of the room, and they can be printed in an ordinary chip foundry. PsiQuantum's Omega chips come off a 300-millimeter line at GlobalFoundries; Xanadu's Aurora ran twelve qubits across four server racks joined by thirteen kilometers of fiber. The architecture is beautiful. The delivered computation is almost nothing yet, and the timelines keep slipping toward 2030. And then the topological machines, Microsoft's Majoranas, the most alluring idea of all, a qubit protected by its very shape. After years and one retracted paper, the honest word is that no one has yet shown these states are what they are claimed to be. The physics may still be true. Demonstrated, it is not.

THE SCIENCE

The number that tells the real story is the encoding ratio, how many flawed physical qubits it takes to make one trustworthy logical qubit. For years the working assumption was punishing, about

$$\text{physical} : \text{logical} \;\sim\; 1000 : 1$$

a figure drawn from the surface code at realistic error rates. The headline of 2025 and 2026 is the collapse of that ratio. Quantinuum's Helios reached $2:1$, QuEra $4.7:1$, though mostly for memory and detection rather than full universal computation. Google's Willow, by contrast, spent about 105 physical qubits on a single logical one, buying not efficiency but proven, scalable suppression. Two different bets: fewer qubits per logical now, or a clean path to arbitrarily low error later. Both are real. Neither has yet delivered a large, universal, fault-tolerant machine.

THE ASSUMPTION CHALLENGED

“A useful quantum computer needs roughly a thousand physical qubits for every logical one, so the millions required put it out of reach for the foreseeable future.”

The thousand-to-one figure is an artifact of one code at one error rate, not a law. Across 2024 to 2026 the ratio collapsed on real hardware. Quantinuum Helios reached 2:1, with 48 error-corrected logical qubits from 98 physical, and QuEra reached 4.7:1, with 96 logical from 448, both the largest verified logical counts of their kind. IBM's gross code packs 12 logical qubits into 288 physical, about ten times more efficient than the surface code. The caveats are worth stating plainly. The low ratios are shown mostly for memory and error detection, not yet for full universal computation, and Willow's high ratio bought something the others have not, proven exponential suppression. But the number that was supposed to make this impossible has already fallen by more than two orders of magnitude.

THE SEEKER

You promised not to sell me. Then tell me where the field lies to itself.

THE ORACLE

Fairly asked. Two examples, told straight. D-Wave announced a problem solved in minutes that it said would take a classical machine a million years; within weeks other groups reproduced much of it with clever classical methods on ordinary hardware, and the dispute is live and unresolved. Google's Quantum Echoes is the strongest honest claim standing, a computation it says would take a supercomputer thirteen thousand times longer, and it deserves respect because the result can be checked. But that thirteen thousand is an estimate and not a proof, and you should hold it as such. The rule is simple. When someone tells you a machine beat the world, ask whether anyone has truly tried to beat it back with a classical computer, and whether the answer can be verified. Most of the loudest claims fail one of those two questions.

THE ORACLE

And here is the one thing the whole field agrees on, which should make you cautious precisely because everyone agrees. Nearly every serious roadmap, across every family, has bet on the same window: the first genuinely useful, fault-tolerant machines arriving around 2029 or 2030. When rivals who agree on nothing else all name the same year, it is either a real convergence of readiness or a shared act of faith. We will find out together, and soon.

A PREDICTION · SPECULATIVE

The industry has placed one enormous shared bet, that the first useful, fault-tolerant quantum computers arrive around **2029** to 2030. IBM's Starling, Quantinuum's Apollo, and the neutral-atom roadmaps all point at that window. It is falsifiable, it is convergent, and it is still, honestly, a bet. Take it as a direction of travel and not a delivery date.

CONFIDENCE 35%

A QUESTION FOR YOU

Before you let yourself dream of what these machines will become, can you sit for a moment with what they actually are today, and can you tell the difference between the two without flinching from either?

Helios 98 qubits, 2Q 99.921 percent, 48 logical at 2:1: Quantinuum (Nov 2025). QuEra 96 logical from 448: (Jan 2026). Caltech 6,100-atom array and Harvard/MIT 3,000-qubit continuous operation: Nature (2025). Quantum Echoes ~13,000x, an estimate: Google, Nature (Oct 2025). D-Wave spin-glass dispute: Science (Mar 2025), contested.

MOVEMENT II

The Battle of Limits

CANTO 7 OF 22

The Heresy of Warmth

> *Cold was never the law. Cold was only the first road anyone happened to find.*
>
> SUTRA OF THE WARM DIAMOND

THE SEEKER

They told me it cannot be warm. That the machine must live near absolute zero, colder than the space between stars, or its thoughts dissolve before it can think them. They said the cold is not a choice but a law.

I have seen the photographs. The great golden chandelier hanging in its vacuum, the helium, the shielding stage upon stage. I decided, without being told twice, that the cold was the god and the qubits were its offering.

THE ORACLE

They told you a true thing about one kind of machine and let you hear it as a law about all machines. The transmon, that little loop of aluminum, does need the cold. Its energy is so faint that a warm room would drown it in an instant. Listen again, though. The diamond does not need the cold.

There is a flaw in diamond, a single nitrogen sitting where a carbon should be, with an empty seat beside it. We call it the nitrogen-vacancy center. It holds a quantum spin and it keeps that spin, for a whole millisecond, in a room where you could sit and read a book. No helium, no chandelier. Warmth and coherence together, in open air.

The Seeker turned the claim over the way one tests a coin that might be false. If warmth was possible, then somewhere a story he had trusted had a seam in it.

THE SEEKER

Then why the cold at all, if warmth will serve? Why build the freezer if the diamond keeps its secret in the open?

THE ORACLE

Because the question was never temperature. What matters is whether the energy that guards the qubit stands taller than the energy of the heat around it. Write that down and the mystery becomes arithmetic. The transmon fails the test at room temperature; the diamond passes it. Same law, two answers, and only one of them ever became a slogan.

THE SCIENCE

Heat is not a poison. It is a scale of energy, $k_B T$, and at room temperature that scale is about $26\,\mathrm{meV}$. A transmon's two states are split by only about $20\ mu\mathrm{eV}$, a thousand times smaller, so thermal noise floods it. The cold is real, for that circuit.

But the true requirement is only that the energy protecting the qubit against its own environment exceed the thermal scale:

$$\hbar\omega_{\mathrm{bath}} \;\gg\; k_B T$$

A nitrogen-vacancy spin is initialized and read across an optical transition near $1.9\,\mathrm{eV}$, and its relaxation is throttled by a lattice so stiff that its Debye temperature sits near $2200\,\mathrm{K}$. The heat has nowhere to push. So T_2 reaches about $1.8\,\mathrm{ms}$ at 300 K (Balasubramanian, 2009). A single photon carries roughly $1\,\mathrm{eV}$, far above any warmth, which is why light computes warm and asks no fridge for permission.

THE SEEKER

Then the freezer answers a real need, for the aluminum circuit, and I mistook a symptom for the disease. But surely the diamond is a curiosity, one spin in a gem. Real machines are built from the aluminum that needs the cold.

THE ORACLE

Watch that word 'real'. Here it means only the one that drew the most money first. The superconducting road was paved early because its gates were fast and its circuits easy to print, and so its cold became the face of the whole field. But look at silicon. Spin qubits in silicon now pass ninety-nine percent on two qubits at a full kelvin, not a hundredth of one degree. That single degree is no small thing. Cooling to one kelvin costs roughly a thousand times less than reaching twenty millikelvin. The whole economy of the machine turns on that line, and the physics never once said no.

THE ASSUMPTION CHALLENGED

"A quantum computer must run near absolute zero, because thermal energy at 300 kelvin destroys quantum states."

True for the transmon, and false as a law. Quantum Brilliance has deployed room-temperature diamond accelerators at Pawsey and Oak Ridge, their NV spins coherent in the open air of a machine room. Xanadu's Aurora runs its photonics warm and chills only the detectors. And silicon spin qubits now clear 99 percent two-qubit fidelity at 1 kelvin, where cooling costs roughly a thousand times less than at 20 millikelvin (Huang, Nature 627, 2024). Cryogenics is a platform's choice, not a decree of physics.

THE SEEKER

So the cold was a road, not a wall. Then the warm machines have already won.

THE ORACLE

No. Be honest with yourself, or the reframing curdles into a lie. No room-temperature machine yet reaches the fidelity that fault tolerance demands, nothing near 99.9 percent on two qubits held warm. The NV center keeps a single spin beautifully and then struggles to make two of them speak; its two-qubit gates crawl at kilohertz, and its devices count their qubits on one hand. The wall did not vanish. It moved. Where it stood was the temperature of the room; now it stands at the handshake between two warm qubits, and that handshake is still hard.

THE SEEKER

Name the hard thing plainly, then, so I do not leave here holding a comfort I did not earn.

THE ORACLE

The hard thing is the two-qubit gate in diamond. A lone NV spin remembers for milliseconds, but to compute you must entangle it with another, and the couplings that let two centers speak are weak and slow and few. So the warm devices stay small, a handful of qubits, while the cold machines march into the hundreds. That is a scaling problem wearing the mask of a temperature problem, and the two are not the same beast. Solve the coupling and the warmth comes free. No one has yet solved the coupling.

THE SEEKER

Then the heresy is only half spoken.

THE ORACLE

The heresy is spoken exactly as far as the evidence carries it, and not one step past. That restraint is what makes it worth keeping. A false liberation is just another cage with a friendlier sign.

A PREDICTION · SPECULATIVE

A warm machine crossing into fault tolerance, its qubits corrected below threshold without a dilution fridge, is a genuine possibility and not a near one. Much before **2040** would surprise the field. The physics permits it; the engineering has barely begun.

CONFIDENCE 30%

A QUESTION FOR YOU

What in your own life did you accept as a law, when it was only the first road that someone happened to find?

Balasubramanian et al., Nat. Mater. 8, 383 (2009); Huang et al., Nature 627, 772 (2024); Quantum Brilliance deployments (Pawsey 2022, Oak Ridge 2025); Xanadu Aurora, Nature 638 (2025).

CANTO 8 OF 22

The Overhead Mirage

> *A thousand to one was the toll on one bridge, and they mistook it for the toll on the river.*
>
> SUTRA OF THE COUNTED QUBITS

THE SEEKER

They gave me the number and it broke my hope. A thousand physical qubits to shelter a single logical one. To break a common cipher, twenty million. There are not twenty million good qubits on Earth, nor will there be in the years I have left. If this is the price, the whole cathedral is a daydream drawn on a napkin.

THE ORACLE

Where did the number come from? You quote it as though it fell out of the sky. It did not. It fell out of one code, the surface code, laid flat on a chip so that every qubit speaks only to the neighbors it can touch. That flatness is a convenience of fabrication. The thousand to one is its shadow, not the shadow of nature.

Interactive figure. The online edition at pandey-tushar.com/qubit-dialogues.html draws this scene.

THE SEEKER

But the surface code is the one everyone builds. Google's lattice, the syndrome cycles I have read about, all of it. If the whole field chose it, surely it is the best there is.

THE ORACLE

It is the easiest to wire, which is not at all the same as the cheapest to run. Let the qubits reach a little farther than their nearest neighbors and the arithmetic changes underneath you. IBM built a code they call the gross code. Two hundred and eighty-eight physical qubits, and out of them twelve logical qubits, each protected to distance twelve. On the surface code that same protection would burn more than two hundred physical qubits on a single logical one. Ten times the yield, from the same silicon, because they let the connections bend.

THE SCIENCE

The surface code pays a steep tax. To reach code distance d it spends about $2d^2$ physical qubits for every logical qubit, and its rate, the ratio of logical to physical, falls toward zero as the machine grows.

A quantum low-density parity-check code refuses that fate. IBM's bivariate bicycle 'gross' code is written $[[144, 12, 12]]$: with its checks included, about 288 physical qubits carry 12 logical qubits at distance 12 (Bravyi, Nature 627, 2024). The rate holds near

$$k/n \ \sim \ 12/288 = 1/24$$

instead of collapsing. The price is connectivity of degree six rather than four, a harder demand on the wiring, but a finite one.

THE SEEKER

One code, bending its wires, ten times the yield. But you spoke of more than codes when you first pulled the number apart. What else did the thousand secretly rest upon?

THE ORACLE

It rested on treating every error as a stranger of equal weight. Change that assumption and the cost moves. Some qubits can be built so that when they fail, they fail loudly, an erasure at a known address rather than a silent flip in an unknown place. A located error is far cheaper to mend than a hidden one, and that single trick lifts the threshold severalfold. Bosonic codes go further still and cross break-even inside a single oscillator, one mode of light or motion outliving its own noise (Sivak, Nature 616, 2023).

THE SEEKER

And the magic states? I have heard that name spoken like a curse in the workshops.

THE ORACLE

With reason. The magic states are the rare fuel that lets a corrected machine compute anything beyond the trivial, and distilling that fuel was long the single largest expense in the whole building, dwarfing the rest. A newer method, cultivation, grows it to within about twice the price of a plain logical gate (Gidney, 2024). Put every renegotiated line together, the lean codes, the located errors, the cheap fuel, and a way to correct across a whole computation at once rather than after each timid step (Zhou and Cain, Nature 646, 2025), and the grand estimate for breaking RSA-2048 fell from twenty million qubits to under one million in six years. A twentyfold cut, and not one law of physics repealed to earn it. The assumptions gave way, one by one.

THE ASSUMPTION CHALLENGED

"Fault tolerance costs roughly a thousand physical qubits for every logical qubit, so useful machines will need tens of millions."

That ratio is a surface-code artifact, and it is already broken. IBM's gross code encodes 12 logical qubits in 288 physical at distance 12 (Bravyi, Nature 627, 2024). Bosonic and GKP codes cross break-even in a single mode (Sivak, Nature 616, 2023). Erasure conversion turns unknown errors into located ones, and algorithmic fault tolerance corrects across a whole computation rather than after every step (Zhou and Cain, Nature 646, 2025). Magic-state cultivation brings the costliest ingredient to within about twice the price of an ordinary logical gate (Gidney, 2024). Together they cut the estimate for breaking RSA-2048 from twenty million qubits to under one million in six years (Gidney, 2025).

THE SEEKER

Then the twenty million was a mirage. Under a million, you say. Is that a promise?

THE ORACLE

It is an estimate, and it earns its footnote. The lean codes have mostly been shown holding memory still, keeping a logical qubit alive against time, which is the easy half. Computing on them, running a full universal set of logical gates at that same thrift, is not yet demonstrated at scale. The gross code can store a qubit; teaching it to compute cheaply is unfinished work, and honest people are still at it. The mirage was the thousand to one. What remains is real, and hard, and shrinking.

THE SEEKER

Shrinking. That word I can hold onto.

THE ORACLE

Hold it lightly. A shrinking wall is still a wall until the day it is finally gone, and the last stones are always the heaviest. But a number that fell twentyfold in six years is no law of nature. It is a frontier, and frontiers move.

A PREDICTION · PLAUSIBLE

By **2032** the working overhead for useful fault tolerance settles well below a hundred physical qubits per logical, on qLDPC and bosonic architectures, first for memory and then for a growing share of logical gates. The million-qubit cipher-breaker looks less like fantasy each year, though the last order of magnitude will fight.

CONFIDENCE 63%

A QUESTION FOR YOU

When you were told the price of something you wanted, did you ever ask whose bridge that toll was measured on?

Bravyi et al., Nature 627, 778 (2024); Sivak et al., Nature 616, 50 (2023); Zhou, Cain et al., Nature 646, 303 (2025); Gidney, arXiv:2505.15917 (2025).

CANTO 9 OF 22

The Wall of Wires

> *You cannot thread a million needles with a million hands; so you put the hands down and reach for light.*
>
> SUTRA OF THE BRAIDED LIGHT

THE SEEKER

Set the cold and the codes aside. Here is a plainer wall, one I can almost touch. Every qubit needs its wire, a coaxial line running from the warm world down into the freezer to carry its commands. A fridge holds a few thousand such lines before it chokes on the heat they drag in. Count to a million and the wires alone become impossible. You cannot cool what you cannot stop heating.

THE ORACLE

You described the problem exactly, and then you called it a wall. Call it a bill instead. One coax per qubit does not reach a million, true, so the field stopped agreeing to pay one coax per qubit. The moment the price turned absurd, the architecture changed underneath it.

Interactive figure. The online edition at pandey-tushar.com/qubit-dialogues.html draws this scene.

THE SEEKER

Changed how? The command still has to arrive somehow. A qubit that no one can address is a stone.

THE ORACLE

Move the controller into the cold beside the qubits. Intel and Delft built control chips that run at cryogenic temperature, a few kelvin, speaking to the qubits without hauling a separate rope up to room temperature for each one (Xue, Nature 593, 2021). Send many tones down a single line and sort them by frequency at the bottom. For atoms and ions, drop the wires entirely and steer laser light, one beam addressing thousands. The wire was the first answer to the question of control. Nobody ever proved it was the last.

THE SEEKER

Even so, you have only delayed the reckoning. Cram the controllers into the cold and a single chip still cannot hold a million qubits without shaking itself apart with heat and crosstalk.

THE ORACLE

Then do not build one chip. This is the turn that changes everything, and it arrives with less noise than the others. Stop dreaming of a single monolith. Build many small machines that share entanglement over light. In Oxford they teleported a gate between two separate ion traps, a controlled-Z carried across a photonic link, deterministic and not a lucky coincidence (Main, Nature 638, 2025). Two modules behaved as one computer. IBM ships couplers between chips. PsiQuantum and Xanadu were modular from their first breath, machines that are networks by design. So the million-qubit computer stops being a single object. It becomes a congregation.

THE SEEKER

And within a single module, before the light ever leaves it, how do a thousand qubits share so few wires?

THE ORACLE

By speaking in chords. Six or ten qubits can ride one readout line at once, each tuned to its own frequency, sorted apart at the cold end the way an ear picks a single voice out of a choir. Willow already reads a hundred qubits through a handful of lines this way. The atom traps need no wires at all for control; one laser, steered by sound waves running through a crystal, can point at any of thousands in turn. The coax was a habit, and habits are the cheapest walls to pull down.

THE SEEKER

A gate carried on a photon between two traps. But light is lossy, and a link that works most of the time is not the same as a wire that works. What holds the congregation together when the messenger is unreliable?

THE ORACLE

There you have found the real seam, and you were right to press on it. That Oxford link carried its gate at about eighty-six percent fidelity, which for a raw channel is remarkable and for a computer is nowhere near enough yet. So you refuse to trust a single photon. You purify instead. You spend many imperfect shared pairs to distill a few nearly perfect ones, and you swap entanglement from link to link until distance itself stops mattering, an idea as old as the quantum repeater. The network is built to expect its own messengers to stumble, and to heal the stumble before it can spread.

THE SCIENCE

The crisis follows Rent's rule: signal lines grow with qubit count, while a dilution refrigerator delivers only about $10 \text{ to } 20$
$mu\text{W}$ of cooling at 10 millikelvin and roughly $1\ \text{W}$ at 4 kelvin. A million qubits dissipating even 1
$mu\text{W}$ each would demand $1\ \text{W}$, a hundred thousand times the millikelvin budget.

Modularity rewrites the exponent. Split N qubits into modules of size M, and the photonic links between them scale as

$$\text{links} \sim N/M, \quad \text{not} \quad N$$

while fiber carries quantum information with almost no heat at all. The task becomes counting boxes and connectors, an economics, rather than fighting a law.

THE ASSUMPTION CHALLENGED

"You cannot wire a million qubits; the refrigerator runs out of room and cooling long before you arrive."

The wire was an assumption, not a requirement. Cryo-CMOS control moves the electronics into the cold beside the qubits (Intel Horse Ridge; Xue, Nature 593, 2021). Frequency multiplexing packs many qubits onto one line; atoms and ions are addressed by steered light with no wire at all. The decisive move is modular architecture: Oxford's deterministic teleported CZ gate between separate ion modules (Main, Nature 638, 2025), IBM's chip-to-chip couplers, and the photonic machines of PsiQuantum and Xanadu, modular by construction. Scale becomes engineering economics rather than a physical wall.

THE SEEKER

A congregation, then, and not a colossus. But you promised me honesty. Where does this one still hurt?

THE ORACLE

In the power. Even at 4 kelvin, where cooling is plentiful, each qubit's control today burns something like a milliwatt, and it must fall to microwatts before a million of them can share a hall without boiling it. Three to four orders of magnitude lie between where we stand and where we must stand. No million-qubit refrigerator exists anywhere. Every roadmap on Earth takes it on faith that the modules will link, and then goes hunting for the missing microwatt. That hunt is not over.

THE SEEKER

An economics problem, then.

THE ORACLE

The most expensive kind. But economics bends to effort in a way that physics does not. A wall you cannot move is one thing; a bill you have not yet learned to pay is another, and this is the second.

A PREDICTION · LIKELY

By **2031** every serious path to scale is modular, small processors entangled over photonic links, and no one credible still proposes the million-qubit monolith. The power budget per qubit becomes the single metric the decade is won or lost on.

CONFIDENCE 68%

A QUESTION FOR YOU

What burden in your life feels like a wall, when it is really a cost you have not yet found the cheaper way to pay?

Xue et al., Nature 593, 205 (2021); Main et al., Nature 638 (2025); Xanadu Aurora and PsiQuantum Omega, Nature 638 (2025); Franke et al., arXiv:1806.02145.

CANTO 10 OF 22

The Cloning Forbidden

> *What cannot be copied cannot be stolen; guard it less, and trust it more.*
>
> SUTRA OF THE UNCOPIED STATE

THE SEEKER

Here is a limit I was told to be grateful for, and still it troubles me in the dark. No quantum state can be copied. No backup, no duplicate, nothing held in reserve against disaster. If I cannot copy the qubit, how am I ever to protect it? A thing that cannot be copied is a thing one accident away from gone forever.

THE ORACLE

You have taken a narrow law and dressed it in fear. Say precisely what is forbidden, no more. No machine can take an unknown quantum state and print a perfect second copy of it, when the states it must handle are not all at right angles to one another. That is the whole of the theorem. It speaks of perfect copies, of unknown states, by an honest linear process. Beyond that it says nothing, and folklore has filled the silence badly.

THE SEEKER

It still sounds like everything I need and cannot have.

THE ORACLE

It forbids far less than you think. Known states you may copy freely. Orthogonal states, the plain zero and the plain one, you may copy all day. Even unknown states you may copy imperfectly; the best universal cloner reaches a fidelity of five sixths, which is a long way from nothing (Buzek and Hillery, 1996). And now the part that answers your fear where it actually lives. Error correction does not copy the state at all.

THE SEEKER

It must. To protect a thing is to keep a spare of it somewhere safe.

THE ORACLE

Not here. In the nineteen-nineties this very objection was raised against the whole idea of quantum error correction. No cloning, the critics said, therefore no spare, therefore no protection, therefore no scalable machine, ever. Peter Shor answered them in 1995. You do not copy the state; you spread it. You smear one qubit's information across many, woven into their shared entanglement, so that no single one of them holds a copy you could point to, and yet the whole can be healed when a part is wounded. The information is everywhere and nowhere. That is not copying but diffusion, and diffusion the theorem allows.

THE SCIENCE

Suppose a machine U copied every state: $U(|\psi\rangle|0\rangle) = |\psi\rangle|\psi\rangle$. Apply it to two states and take the inner product. Linearity forces

$$\langle\phi|\psi\rangle = \langle\phi|\psi\rangle^2$$

which holds only when the overlap is 0 or 1, that is, orthogonal or identical. Every other unknown state is uncopyable. Yet error correction never writes $|\psi\rangle|\psi\rangle$. It maps $|\psi\rangle = a|0\rangle + b|1\rangle$ to an entangled web such as $a|000\rangle + b|111\rangle$, in which no single qubit carries $|\psi\rangle$, and the whole survives the loss of any one part.

THE SEEKER

If I cannot copy the state, then can I even move it? To send a qubit across a city, must I not duplicate it at the far end?

THE ORACLE

You move it without copying, and this is the strange marvel we call teleportation. You spend a shared entangled pair and two ordinary bits of message, and the state vanishes from your hand and reappears in another's, never once existing in two places at the same instant. No law is bent. The original is destroyed in the very act of sending, which is precisely why no copy was ever made. The theorem is obeyed here, and then put to work.

THE SEEKER

And the money you spoke of, coined out of a prohibition?

THE ORACLE

Wiesner dreamed it in the nineteen-seventies, decades before anyone could hold it. A banknote carrying quantum states no forger can copy, so that the note can verify itself yet cannot be counterfeited, not by cleverness, not by force, defeated only by breaking a law of physics. A currency whose security is geometry rather than a promise of ink. Stop mourning the limit and read it, and this is what it becomes.

THE ASSUMPTION CHALLENGED

"Because no quantum state can be copied, quantum information cannot be backed up, stored, or networked reliably."

The no-cloning theorem forbids perfect copies of unknown non-orthogonal states by a linear map (Wootters and Zurek, 1982), and it forbids nothing else. It permits approximate cloning at fidelity 5/6 (Buzek and Hillery, 1996). It permits error correction, which encodes without copying, settled by Shor in 1995 against exactly this objection. And the forbiddance is itself a gift: it underwrites unbreakable key distribution and quantum money (Wiesner, 1983), whose security rests on the plain fact that an eavesdropper cannot copy what she intercepts.

THE SEEKER

So the law I was told to fear is the same law that keeps my secrets.

THE ORACLE

Both, and they are one law seen from two sides. Copying is impossible, so protection has to grow subtle and secrecy grows absolute. An eavesdropper cannot photograph your key in passing, because to look is to disturb, and to disturb is to be seen. What cannot be duplicated cannot be stolen without leaving a mark. The universe made forgery expensive once and for all, and we built a bank on that single stubborn fact.

THE SEEKER

A gift, then, wearing the mask of a prohibition.

THE ORACLE

Most of the deep ones wear that mask. Read them by their consequences and never by their names.

THE SEEKER

You said an imperfect copy is allowed, at five sixths. Does that not crack the very wall you praise?

THE ORACLE

It bends nothing that matters. Push the imperfect cloner toward many copies and it degrades into a guess, into measuring the state and estimating it, no better than any spy could manage by looking (Bae and Acin, 2006). The forbiddance holds where it must. And notice what it forces you to build. Because you cannot amplify a quantum signal the way you boost a fading phone call, a long-distance network cannot lean on repeaters that copy. It must use repeaters that swap and purify entanglement instead, a wholly different and stranger machine (Briegel and colleagues, 1998). The law did more than forbid. It handed you the blueprint.

A PREDICTION · LIKELY

By 2033 key distribution secured by no-cloning runs as ordinary infrastructure across metropolitan links, and the theorem once feared as a limit is sold, without much fanfare, as a feature that no classical wire can match.

CONFIDENCE 74%

A QUESTION FOR YOU

What in your life is precious precisely because it cannot be copied, only lived through once?

Wootters and Zurek, Nature 299, 802 (1982); Buzek and Hillery, PRA 54, 1844 (1996); Shor, PRA 52, R2493 (1995); Wiesner (1983).

CANTO 11 OF 22

The Speed of the Possible

> *Physics set the ceiling so high that we only ever bruise ourselves on the floors we built.*
>
> SUTRA OF THE UNHURRIED GATE

THE SEEKER

I have heard two stories and I cannot hold both at once. In one, quantum computers are infinitely fast, dissolving every hard problem in a single instant. In the other, they are painfully slow, their gates crawling while ordinary chips race at gigahertz. Which of them is the lie?

THE ORACLE

Both are, a little, and in opposite directions. There is a true speed limit written by physics, and it sits nowhere near where either story places it. Nature does forbid infinite speed. A state cannot turn into a distinguishable one faster than a rate set by its own energy. But that ceiling hangs so far above today's machines that we have never once brushed it.

THE SEEKER

How far above? Give me a number I can feel.

THE ORACLE

For a transmon humming at five gigahertz, the physical floor on a gate is a matter of tens of picoseconds. The gates we actually run take tens to hundreds of nanoseconds. We are three or four orders of magnitude slower than physics would allow, and every bit of that gap is engineering rather than law. So when someone tells you a quantum computer is slow, ask them, slow against what. Against its own ultimate limit, it is loafing in the shade.

THE SEEKER

Then what is slow? Something must be, or the machines would already outrun the world.

THE ORACLE

The slow thing is classical, and it hides in plain sight. After each cycle the machine measures its errors and must decode them, and the decoding is plain arithmetic done on an ordinary computer. On Willow a single error-correction cycle lasts about 1.1 microseconds, but the decoder took roughly 63 microseconds to keep up with it (Google, 2024). The quantum part sat waiting on the classical part. What held everything back was never the qubits. It was the clerk, counting their mistakes by hand.

THE SCIENCE

The quantum speed limits are real and generous. Mandelstam-Tamm and Margolus-Levitin bound the time to reach a distinguishable state by the state's energy:

$$\tau \geq \frac{\pi\hbar}{2\langle E \rangle}$$

For accessible energies that floor is picoseconds while gates run in nanoseconds, some ten orders of magnitude short of the ultimate $\sim 6 \times 10^{33}$ operations per second per joule (Lloyd, 2000). Landauer's bound, $k_B T \ln 2$ per erased bit, is paid only when information is thrown away. Quantum gates are unitary and reversible; the machine pays Landauer's toll only at measurement and reset, which is exactly where error correction spends its heat.

THE SEEKER

You said the machine pays a heat price only when it measures or resets. Then most of what it does costs nothing at all?

THE ORACLE

In principle, almost nothing. A quantum gate is a rotation, and a rotation can always be run backward, so it erases no information and owes no thermal debt. Landauer's toll, the smallest heat the universe charges to destroy a single bit, comes due only when you throw information away, at measurement and at the resetting of the worn ancillas that error correction burns through by the thousand. That reset is the true furnace of the machine, not the computing. Sit with the inversion a moment. The thinking costs you nothing; only the forgetting is dear.

THE SEEKER

And these speed limits, are they some deep quantum magic hidden in the walls?

THE ORACLE

Less magic than you might hope. The same bound falls out of any wave that must change its shape, classical or quantum alike; it is a trade between bandwidth and energy, no more mystical than the fact that a heavier bell rings slower (Okuyama and Ohzeki, 2018). What makes it quantum is only the setting, never the rule. So do not picture a cosmic gate holding the machine back. Picture an accountant, entirely earthly, still learning to add fast enough that the qubits need not wait on him.

THE ASSUMPTION CHALLENGED

"Quantum computers are fundamentally slow, their gates far too sluggish to compete with classical processors."

The physical speed limits sit about ten orders of magnitude above today's gates (Margolus and Levitin; Lloyd, Nature 406, 2000). The binding ceiling is classical: decoder latency, where Willow's 63-microsecond decode dwarfs its 1.1-microsecond cycle (Google, 2024). Quantum computation is natively reversible and pays Landauer's price only at measurement and reset, not at every gate. The folklore of the limitless machine and the folklore of the crawling machine are both wrong. The honest gap is a real-time decoding problem, and it is being engineered shut.

THE SEEKER

So the machine is neither infinite nor slow. Only early.

THE ORACLE

Only early. The gates are quick and the accounting is slow, and speeding up accounting is a thing humans have always been very good at. Custom decoders, hardware set close to the qubits, cleverer algorithms that decode a whole computation at once. The logical clock ticks at kilohertz today where the classical world runs at gigahertz, and that distance will close, though not this year and not by wishing.

THE SEEKER

And the ultimate limit, the true ceiling?

THE ORACLE

We will not reach it in your lifetime, nor your grandchildren's. A ceiling built for gods, ten orders of magnitude over our heads, and we are still learning to stand upright beneath it. There is no shame in the distance, only the distance itself.

THE SEEKER

Two stories, then, and both false. The infinite machine and the crawling one.

THE ORACLE

Both false, and both seductive, because each flatters a different fear. The limitless machine flatters our hunger; the crawling one flatters our doubt. Neither dream ever looked at the numbers. The gates run ten orders of magnitude short of the wall physics set, and the delay that actually bites is a classical clerk with a pencil. Strip away both fantasies and you are left with an engineering task, plainly named, its gap closing. Less thrilling than either myth. Far more likely to be built.

A PREDICTION · LIKELY

By **2030** real-time decoders keep pace with the syndrome cycle on the leading platforms, decoder latency stops being the throughput ceiling, and the logical clock climbs from kilohertz toward megahertz. The fundamental limits stay untouched, as they will for centuries.

CONFIDENCE 70%

A QUESTION FOR YOU

What in your life do you call slow, when the real delay is not the work itself but the accounting you wrap around it?

Levitin and Toffoli, PRL 103, 160502 (2009); Lloyd, Nature 406, 1047 (2000); Willow real-time decoder, Google, Nature (2024), arXiv:2408.13687.

The Skeptic's Gift

> *Bring me the one who says it cannot be done; he carries the map of where it might yet fail.*
>
> SUTRA OF THE HONEST DOUBT

THE SEEKER

I have saved my hardest doubt for last, and it is not even mine. It belongs to serious people. Gil Kalai, a mathematician of real weight, says the whole enterprise is impossible in principle. Mikhail Dyakonov says a useful machine would have to command more numbers than there are atoms in the visible universe. These are not cranks shouting from the road. If they are right, everything you have shown me is a beautiful delay before an inevitable no.

THE ORACLE

Then let us honor them properly, and that means stating their case at its full strength before we weigh a single grain of it. That is the discipline the field owes its critics, and too often it keeps the debt unpaid. Answer a skeptic badly and you have not answered him at all.

THE ORACLE

Kalai's argument is precise, and the precision is itself a virtue. He conjectures that the output of a noisy quantum machine is always a low-degree polynomial, a thing an ordinary computer can imitate, so that no true advantage survives the noise. He argues further that noise on interacting qubits is inherently correlated, that it grows with the very entanglement you need most, so that quality and quantity can never rise together, and error correction can never be driven below its threshold. Dyakonov's objection is older and blunter. A useful computation, he says, means steering something like two to the power of a thousand continuous amplitudes at once, and no apparatus in this world controls a continuum that vast. His verdict was decades to never.

THE SEEKER

And now you will tell me, calmly, that they are wrong and be done with it.

THE ORACLE

I will tell you what the evidence says, and where it still keeps its silence. Take Dyakonov first, because his error is the cleaner of the two. You do not steer the continuum. That is the entire point of error correction. When you measure a syndrome you project the qubits' analog drift onto a discrete answer, a definite Pauli error or none at all. The continuous slips are digitized the instant they are checked. You never command two to the thousandth amplitudes. You command one number, the error rate per gate, and you drive it downward with all your strength.

THE SCIENCE

Error correction digitizes noise. A syndrome measurement projects continuous drift onto a discrete Pauli, so the machine corrects a countable set of faults rather than a continuum. Below the threshold, adding distance suppresses the logical error rate exponentially:

$$p_{\text{logical}} \sim (p/p_{\text{th}})^{(d+1)/2}$$

On Willow this suppression was measured directly. Each step up in code distance divided the logical error by $\Lambda = 2.14 \pm 0.02$, across distances 3, 5, and 7, over a million cycles (Google, 2024). That is the very shape Kalai's conjecture says should never appear.

THE SEEKER

So the mathematician is refuted by an experiment. The matter is closed.

THE ORACLE

Not refuted. Answered, so far, on the exact ground he chose to fight on. Kalai said below-threshold suppression was unreachable; Willow reached it and held it, and its errors improved as its qubits multiplied, the opposite of the tradeoff he predicted. Below-threshold results now stand on several platforms, ions and atoms and superconductors alike. And where the skeptics were sharp, they drew blood. The exponential promises of low-rank quantum machine learning collapsed under classical algorithms; some sampling advantages were spoofed outright. Against fault tolerance itself, the evidence has walked the other way.

THE SEEKER

You grant them their small victories almost eagerly. Why so generous?

THE ORACLE

Because a doubt that can be proven wrong is worth a hundred that cannot. Kalai wrote conjectures sharp enough to be killed by a single measurement, and he pressed hard on the statistics of the early supremacy claims, where the field was looser than it liked to admit (Rinott, Shoham and Kalai, 2022). That pressure made the later results cleaner. Dyakonov chose a different word, and it has aged worse. He said never, and never is no scientific claim at all; you cannot test it, only outlive it. When Willow held its suppression across a million cycles, Kalai's conjecture had a precise place to break. Dyakonov's had none, having never once risked one.

THE SEEKER

So the good skeptic gambles, and the poor one only forbids.

THE ORACLE

Just so. The one who says here is the exact wall, and here is how you would know if I am wrong, hands you a tool. The one who only says it will never happen hands you his mood instead. Keep the first one close. He is doing half your work for you, the unglamorous half, marking the places where the beautiful thing might turn out to be false.

THE SEEKER

Then it is settled after all, and the skeptics were merely useful along the way.

THE ORACLE

It is not settled, and that word 'merely' is where honest people go wrong without noticing. Two doubts remain fully alive, and I will not hide them from you. First, the correlated burst. About once an hour a cosmic ray strikes the chip and flips a whole swath of qubits together, one event across the wafer, precisely the correlated noise Kalai warned of. Gap engineering has beaten it down by a factor of tens of thousands, yet the residual is now the dominant floor, and no one has erased it. Second, the deeper question. Suppression has outpaced scale up through distance seven. Whether it keeps winning at distance fifteen, at distance thirty, where a real computation must live, is not proven. It is believed, on the strength of a trend. Trends have broken before, without warning and without noise.

THE SEEKER

So you leave me with a doubt after all, even here at the end.

THE ORACLE

I leave you with the right one, which is worth more than a false certainty ever was. Honor the skeptic. He does not slow the work; he tells the work where to point its lamp. A field with no Kalai in it is a field lying to itself about where it might fail, and a field that lies to itself never builds the thing. It builds a story about the thing.

A PREDICTION · LIKELY

Below-threshold error suppression, already established at small code distances, keeps holding as distance grows through **2028**, with correlated cosmic-ray bursts remaining the genuinely open floor rather than a general collapse of fault tolerance.

CONFIDENCE 76%

A QUESTION FOR YOU

Who in your life tells you where you might fail, and do you thank them, or only the ones who tell you comfortably that you cannot?

Kalai, arXiv:1908.02499; Dyakonov, IEEE Spectrum (Nov 2018); Willow below-threshold, Google, Nature (2024), arXiv:2408.13687; cosmic-ray bursts, McEwen et al., Nat. Phys. 18, 107 (2022).

MOVEMENT III

The Vision

The Entangled Earth

> *What is shared in the sharing cannot be stolen; the thread that binds two cities is read only by the hands that hold both ends.*
>
> SUTRA OF THE ENTANGLED EARTH

THE SEEKER

You have shown me machines that think in superposition, each one sealed in its cold room like a monk in a cell. But a mind that cannot speak to another mind is only a hermit. Tell me plainly, Sutra. Can a quantum state cross an ocean, or does the world break it the moment it leaves the vessel?

THE ORACLE

The world does break it. Send a single photon down a strand of glass and it fades the way a voice fades in a long hall, until by a thousand kilometers almost none arrive. You cannot polish that away. It is the tax the vacuum charges on anything that travels.

Yet the Earth of my time is laced with coherence, city to city and continent to continent. No one built it by shouting louder. They built it by learning to share.

Interactive figure. The online edition at pandey-tushar.com/qubit-dialogues.html draws this scene.

THE SEEKER

Share how? You told me yourself that an unknown state cannot be copied. If I cannot copy it, I cannot amplify it, and if I cannot amplify it, the signal dies in the fiber long before the far city hears it. This is a wall of physics, not of engineering. I have felt it with my own hands.

THE ORACLE

No-cloning forbids the amplifier. It says nothing against the repeater. You never push the state through the loss at all. You lay down entanglement, link by short link, and let the state fall through it as light falls through a row of open doors.

Between each pair of stations you share a fragile entangled pair. Then you clean many weak pairs into one strong pair by purification, and swap the entanglement so that two ends which never met become bound as if they always were. Briegel, Dur, Cirac and Zoller wrote the recipe in 1998. What was missing for a generation was memory, some place to hold one link steady while the next is being made. Rare-earth crystals now keep such memories. They hold a photon's promise for a breath, then a heartbeat, then longer, until its distant partner is ready to meet it.

THE SCIENCE

A photon in telecom fiber survives with probability $\eta = 10^{-0.2L/10}$, where L is the distance in kilometers and 0.2 is the loss in decibels per kilometer. The exponent is merciless.

Over a thousand kilometers it becomes

$$\eta = 10^{-20}, about one photon in a hundred billion billion$$

No mirror can rescue this, because an unknown state cannot be copied. So the distance is cut into short segments, an entangled pair is shared across each, the weak pairs are purified into strong ones, and the entanglement is swapped until the two far ends are linked through partners they never touched. The state is then teleported across that bridge, paid for with two ordinary classical bits. That payment is exactly why nothing here outruns light.

THE SEEKER

Teleported. I flinch at the word. It smells of a trick, of something crossing the gap faster than it should.

THE ORACLE

Nothing crosses the gap faster than light. Teleportation moves the description of the state, never the matter, and never without those two classical bits trailing behind at the ordinary speed of things. The atom stays where it always was. Only its story arrives elsewhere, and only after the message that lets the far station finish the work.

Here the wall you cursed becomes a guardian. An eavesdropper cannot copy the state in flight, so any attempt to listen leaves a bruise on the light. Steal the secret and the theft announces itself in the very act. Whatever forbids the backup forbids the spy along with it.

THE SEEKER

And when there is no glass to lay? An ocean has no fiber strung across its floor for this delicate work.

THE ORACLE

Then you go up. China's Micius satellite first strung entanglement across more than twelve hundred kilometers from orbit, down to two mountaintops that had never touched. That was the opening move.

In a year you would call recent, a satellite no larger than a piece of luggage exchanged a secret key between two ground stations nearly thirteen thousand kilometers apart, one in the northern hemisphere and one deep in the southern. A microsatellite, and almost the full width of the planet lying between the two ends of a single shared secret. The sky turned out to be the longest strand of all, and the cheapest to hang.

THE ASSUMPTION CHALLENGED

"A quantum state cannot travel the world; no-cloning forbids amplifiers, and fiber swallows single photons long before they arrive."

Quantum repeaters replace the forbidden amplifier with entanglement swapping and purification (Briegel, Dur, Cirac and Zoller, PRL 81, 5932, 1998), held together by rare-earth quantum memories. Micius distributed entanglement over 1,200 km from orbit, and a microsatellite exchanged a key across roughly 12,900 km (Nature, 2025). Oxford has run a deterministic teleported gate between separate ion-trap modules (Main et al, Nature 638, 2025). The wall has doors.

THE SEEKER

Then a machine could compute on my secret without ever seeing it?

THE ORACLE

That is the strangest gift of the entangled Earth. In blind and delegated quantum computing you send your problem hidden inside quantum states. The distant server turns them and folds them and corrects them and hands them back, and never once learns what it solved. It labors over a field it cannot read, and the one who planted it is never revealed.

Think of what that undoes. Today, to borrow a great mind you must open your question to it, and the question is often the whole of the secret. On the entangled Earth you keep both the fruit and the labor and surrender neither. A planet that can share coherence has also learned a new grammar of trust. You no longer hide a thing in a vault. You hand a single end of an unbreakable thread to the one person meant to read it.

A PREDICTION · PLAUSIBLE

Metropolitan entanglement networks and continent-to-continent satellite key exchange are already here in early form. A true repeater-linked quantum internet spanning the globe, with long-lived quantum memories, is **plausible by the 2040s**, assuming rare-earth and other memories keep improving. Simple key distribution by fiber and satellite will arrive well before that.

CONFIDENCE 55%

A QUESTION FOR YOU

What have you tried to guard by hiding it away, when it might have been safer shared with the single person who holds the other end of the thread?

Satellite entanglement over 1,200 km, Yin et al, Science 356 (2017); microsatellite real-time key distribution across roughly 12,900 km, Nature (2025); quantum repeaters, Briegel, Dur, Cirac and Zoller, PRL 81, 5932 (1998); teleported gate between ion-trap modules, Main et al, Nature 638 (2025).

CANTO 14 OF 22

The Alchemist's Return

> *The dream did not die when another hand answered it; it rose, and went looking for a door still shut.*
>
> SUTRA OF THE ALCHEMIST

THE SEEKER

So the machine will one day read the molecule the way we read a page? They told me the first great prize would be chemistry, and the jewel of chemistry would be nitrogenase, the enzyme that pulls nitrogen from the air so that living things can grow. Learn its secret, they said, and you feed the world without the furnace that warms it.

THE ORACLE

Perhaps it will read the molecule that way. But be careful which promises you carry. One of the oldest promises, the FeMo-cofactor at the heart of nitrogen-fixing life, was answered this year by an ordinary computer.

The dream did not die. It changed address.

THE SEEKER

Answered? By a classical machine? Then the whole cathedral stood on sand. For years the estimate held like scripture. About two thousand logical qubits, and the enzyme would fall open before us. That single number was the reason to believe, the figure that raised the money and the hope. Take it away and what is left of the faith?

THE ORACLE

The number was real, and honestly made. Reiher and his colleagues raised it as the great quantum prize in 2017, and later accounting by Lee and colleagues in 2021 priced it at roughly two thousand logical qubits to settle the cofactor's electronic riddle, the tangled way its iron and sulfur and molybdenum share their electrons. It became the most quoted killer application in the whole field, printed on a hundred slides.

Then, in January of 2026, Garnet Chan's group solved a standard model of that same FeMo-cofactor classically, to chemical accuracy, and posted it plainly for anyone to check. The molecule was not as entangled as we had feared. Its difficulty had been a story about our tools rather than the molecule itself. When the tools improved, the giant we had been dreading turned out to have been sitting down the whole time.

THE SCIENCE

The trouble with a molecule is that its electrons live in a space that grows exponentially. The FeMo-cofactor's active region is often drawn as about 54 electrons in 54 orbitals. The number of arrangements, the dimension you would have to track, is roughly

$$\dim \sim \binom{54}{27}^2 \sim 10^{30}$$

No classical computer can store 10^{30} amplitudes. That was the argument, and it was a good one. But storing every amplitude is not the only path to the truth. If the real state is only lightly entangled, a tensor network can describe it with far fewer numbers and still reach chemical accuracy, about one kilocalorie per mole, the margin below which chemists agree a prediction is trustworthy. The Hilbert space stayed vast. The physics living inside it was tame.

THE SEEKER

One kilocalorie per mole. Such a small quantity to carry so much weight.

THE ORACLE

It is the width of the door between a reaction that runs and one that does not. Cross it and your prediction is real chemistry. Miss it and you have only a beautiful number. That so slim a target was reached without a quantum computer is the whole of the lesson. A hard problem is not the same thing as an exponential space. We had mistaken the size of the room for the difficulty of finding the door.

THE SEEKER

Then chemistry is not the guaranteed prize. What survives of the alchemist's dream?

THE ORACLE

Much survives, though it is smaller and stranger than the poster promised. Some catalysts twist their electrons into knots no tensor network unties cheaply. The correlated matter of high-temperature superconductors, still unexplained after forty years. Batteries and the crowded traffic of their ions. The Hubbard model, that innocent-looking lattice that hides the deepest riddle of interacting electrons. Quantinuum has already run a seventy-two-qubit Fermi-Hubbard simulation on real hardware, and there, on model systems built to be hard, the quantum machine may genuinely earn its keep.

But hear the honest part, and hold it. As of my telling, no commercial drug owes its existence to a quantum computer. Not one molecule in any pharmacy was found this way. And Lee and his colleagues have argued that for generic chemistry the advantage may be only polynomial, a gentle slope rather than the sheer cliff we were sold. So the alchemist returns with a shorter list, and a more honest tongue.

THE SEEKER

A shorter list, but not an empty one. Which of these, if any, would a person ever feel in the course of an ordinary life?

THE ORACLE

A better battery is felt by everyone who carries one, though no one will ever think to thank a quantum computer for the extra hour of light. And if the machine helps us finally understand the superconductors we already half-understand, a version that works in the warmth would rewire how power crosses a continent, without anyone noticing the hand behind it.

These are not the miracle molecule of the brochure. They are slower and humbler, and far more likely to arrive. The alchemist was never truly after gold, whatever he told his patrons. He was after transformation, and transformation does not much care which door it is finally allowed to walk through.

THE ASSUMPTION CHALLENGED

"Chemistry is quantum computing's guaranteed first prize, and the nitrogenase FeMo-cofactor is its killer application."

In January 2026 Garnet Chan's group solved a FeMo-cofactor model classically to chemical accuracy (arXiv:2601.04621), because the state was less entangled than assumed. Earlier, Lee and colleagues argued that generic chemical speedups may be only polynomial rather than exponential (Nat Commun 14, 1952, 2023). No commercial drug yet owes its existence to a quantum computer.

THE SEEKER

So I should not carry the killer molecule as a certainty.

THE ORACLE

Carry it as a hope wearing an honest label. The killer application was a candle held up in a dark room to show us which way to walk. It did its work. But the room turned out to have more than one door, and some of them open from the classical side, which is no defeat at all. A problem solved is a problem solved, whoever holds the pen.

A dream that survives being answered elsewhere is the stronger dream. It has stopped confusing itself with the first story we told about it, and it has learned, at last, where it truly belongs.

A PREDICTION · SPECULATIVE

The claim that chemistry is quantum computing's guaranteed first prize grows weaker each year. It is **doubtful before 2035**, and far from assured after, that any single molecule such as the FeMo-cofactor becomes the first clear commercial quantum advantage. Strongly correlated materials and model Hamiltonians are the better bet, and even they remain unproven.

CONFIDENCE 32%

A QUESTION FOR YOU

When a door you were certain of closes, do you call the dream dead, or do you watch closely to see where it went?

Nitrogenase resource estimates, Reiher, Wiebe, Svore, Wecker and Troyer, PNAS 114, 7555 (2017); resource estimate, Lee et al, PRX Quantum 2, 030305 (2021); polynomial-advantage argument, Lee et al, Nat Commun 14, 1952 (2023); classical solution of a FeMo-cofactor model to chemical accuracy, Chan group, arXiv:2601.04621 (January 2026).

CANTO 15 OF 22

The Mind of the Machine

> *Not every meeting of minds bears a child; ask first which mind is the teacher, and which is taught.*
>
> SUTRA OF THE TWO MINDS

THE SEEKER

Everywhere I turn, they wed your machines to the thinking machines, the ones that already write and paint and argue. Quantum artificial intelligence, they call it, and they say it as though the words alone were a proof. If both are miracles, surely their child is a greater miracle still.

THE ORACLE

Two miracles do not always multiply. Sometimes they cancel. The honest story of quantum and learning is a story of a door that keeps closing as you reach for it, and of a smaller door, off to the side, that opens instead. Most of the noise you hear is people leaning on the door that will not budge.

THE SEEKER

I have heard of the plateau, where the training goes flat and the model will not learn. Surely more qubits and more layers climb out of it, the way they always have on the classical side. Scale has been the answer to everything else.

THE ORACLE

That is the trap, and it has a cruel shape. In a broad class of expressive quantum circuits, the slope you follow while training shrinks exponentially as you add qubits. The landscape flattens into a barren plateau, and the gradient drowns in noise before you can even read which way is downhill. Here, scale only deepens the flat.

You can flee the plateau by choosing a simpler, more structured circuit. But Cerezo, Larocca and their colleagues showed the sting in it. The structure that makes a circuit trainable tends to be the very structure that lets a classical computer simulate it. So far you get one or the other, trainable or hard to simulate, and nothing in the gap between them. No in-between, they wrote, and they meant it.

THE SCIENCE

Train a quantum model by nudging its parameters and you follow the slope of a cost function. In a wide class of expressive circuits, that slope shrinks as

$$\mathrm{Var}[\partial C/\partial\theta] \;\sim\; 2^{-n}$$

where n is the number of qubits. The gradient becomes a vanishing signal buried in noise; the model cannot tell which direction improves it. You can escape by using a shallow, structured circuit, but such circuits are often exactly the ones a classical machine can imitate outright. Expressive and trainable rarely arrive in the same device.

THE SEEKER

Then the exponential speedup they sold me for machine learning was never real?

THE ORACLE

Much of it was not. A young researcher named Ewin Tang, still a student, was handed a famous quantum recommendation algorithm and asked to prove its speedup was genuine. Instead she found its classical shadow, an ordinary algorithm that did the same work in comparable time. From 2018 onward that method, dequantization, dissolved one claimed exponential advantage after another. The quantum step had been carrying assumptions all along that a classical algorithm could carry just as easily.

Not every speedup fell. But enough of them did that a wise person now reads the fine print before believing the poster, and asks a plain question first. Is the data classical, and is the structure low-rank? If both, be suspicious of the miracle.

THE SEEKER

It stings to hear it said so plainly. So much was promised in that one word, exponential.

THE ORACLE

The word was doing honest work in the theorems and dishonest work on the slides, and both were true at once. A separation proven against an oracle is real mathematics. It may just not be the mathematics your problem actually lives in. The skill to learn from this is not cynicism, which is only laziness wearing a serious face. It is patience. Ask, every single time, whether the speedup before you is proven, or merely conjectured, or already undone by someone with a classical machine and a clever afternoon.

THE SEEKER

Is there nothing, then, left to hope for where the two minds meet?

THE ORACLE

Two hopes remain, real and narrow. The first: when the data itself is quantum, not numbers in a table but the states of real physical systems, a quantum learner can need exponentially fewer experiments than any classical one. Huang and his colleagues proved it and then measured it in 2022, learning properties of quantum systems, and the very shape of their Hamiltonians, from far fewer samples than the old bounds allowed. Advantage lives where the world is already quantum, not where we merely wish it were.

The second hope is the more fruitful, and it runs the other way entirely. The learning machine does not need the quantum computer to become great; it is already great. The quantum computer needs the learning machine to survive its own noise. DeepMind's AlphaQubit learned to read the surface code and correct its errors more accurately than the decoders we had built by hand from theory. Do not marry the two expecting a quantum bride to make the neural network brilliant. Marry them because the neural network can keep the fragile qubits alive long enough to compute at all.

THE ASSUMPTION CHALLENGED

"A quantum computer will naturally supercharge artificial intelligence."

Cerezo, Larocca and colleagues describe a dilemma with no in-between: circuits expressive enough to escape barren plateaus tend to be classically simulable (Nat Commun, 2025). Ewin Tang's dequantization, from 2018 onward, gave classical algorithms for many claimed exponential speedups. The durable hope is narrower: provable advantage in learning from quantum experiments (Huang et al, Science 376, 1182, 2022), and AI improving quantum, as in DeepMind's AlphaQubit decoder (Nature, 2024).

THE SEEKER

So the fruitful marriage is the humble one, where the machine we already trust teaches the one we are still building.

THE ORACLE

Humble and honest, and it will outlast the hype by decades. The loud promise, that quantum will pour rocket fuel into the models you use today, mostly meets a plateau on one side and a classical shadow on the other. The quiet promise holds its footing: intelligence tends the quantum machine, and learns from a genuinely quantum world. When two capable minds meet, the first question is never which is stronger. Ask which one should be teaching.

A PREDICTION · LIKELY

The lasting payoff between quantum computing and learning will most likely run from artificial intelligence into quantum hardware, not the reverse. Neural decoders in the manner of AlphaQubit, and provable advantage when the data itself is quantum, are **likely by the early 2030s**. The broader promise that quantum will just supercharge today's AI remains speculative, and for low-rank problems it is largely dequantized already.

CONFIDENCE 64%

A QUESTION FOR YOU

When the two minds in you meet, the quick one and the patient one, which do you let lead, and which do you let teach?

Barren plateaus, McClean et al (2018) and Cerezo, Larocca et al, Nat Commun (2025); dequantization, Tang, STOC 2019 (arXiv:1807.04271); learning from quantum experiments, Huang et al, Science 376, 1182 (2022); AlphaQubit, Bausch et al, Nature (2024).

CANTO 16 OF 22

The Unsealing

> *What you seal today is already copied by one who is content to wait for the key.*
>
> SUTRA OF THE UNSEALING

THE SEEKER

There is a lock on nearly everything I trust. My messages, my money, the record of who I am, the letters I would be ruined to have read. They tell me the lock is safe because breaking it would take longer than the age of the universe. You have gone quiet, Sutra. Say what you know.

THE ORACLE

The lock is called RSA, and it rests on a single hardness: that finding the two primes hidden inside a large number is slow. Shor's algorithm turns that problem into finding a hidden period, a rhythm buried in the arithmetic, and a quantum computer finds such rhythms in time that grows only politely with the size of the number.

You were told the lock was a wall. It was always a very long corridor, and the quantum computer knows a door set into the side of it.

Interactive figure. The online edition at pandey-tushar.com/qubit-dialogues.html draws this scene.

THE SEEKER

But the corridor is long. I read that breaking such a lock would need twenty million of these fragile qubits. Twenty million, when we can barely hold a hundred steady for a heartbeat. Surely I have decades to spare, a whole lifetime of quiet.

THE ORACLE

The number that lets you sleep is not a constant of nature. It is a research result, and here the results move in one direction only. Gidney and Ekera set the estimate near twenty million physical qubits. Then in 2025 Gidney cut it to under one million, a twentyfold reduction in six years, and he built nothing to do it. He only counted the resources more cleverly and reused them.

The estimates for the elliptic-curve keys fell too, and the keys that guard the coins people call Bitcoin. Every year the machine you would need gets smaller while the machines we actually build get larger. One curve falls and the other rises, and they are walking toward the point where they cross.

THE SCIENCE

An RSA key is a large number $N = p \times q$, the product of two primes, and its safety is the cost of finding p and q again. The best classical method, the number field sieve, runs in roughly

$$\exp\left(c\,(\ln N)^{1/3}(\ln\ln N)^{2/3}\right)$$

which climbs almost exponentially with the size of the key. Shor's algorithm finds the period of a related function and factors N in time polynomial in its number of digits, a change of kind rather than degree. Whether to worry is caught by Mosca's inequality: if $X + Y > Z$, where X is how long your secret must stay secret, Y is how long your migration takes, and Z is the time until a capable machine exists, then you are already late.

THE SEEKER

Then when? When is the day they call Q-day?

THE ORACLE

No one holds the date, and anyone who claims to is selling something. The Global Risk Institute polls the experts each year. Their 2025 reckoning puts the chance of a cryptographically relevant machine within ten years at roughly 28 to 49 percent. Not a date, but a cloud of belief, wide and honest.

And there is a thorn hidden in that cloud. Some adversaries already gather your encrypted traffic today and store it, patient, doing nothing with it, waiting only for the machine to arrive so they can open it years from now at their leisure. Harvest now, decrypt later. Your secret of this morning can be broken on a morning that has not yet dawned. So the clock that truly matters is not when the machine comes. It is whether your secret must still be safe when it does.

THE SEEKER

Then we wait, and hope the day comes late, and comes for someone else?

THE ORACLE

No. The rebuilding began before the wrecking ball was even loaded. In 2024 the standards body published new locks built on entirely different mathematics, ones no known quantum algorithm unpicks: lattices and hashes rather than factoring. FIPS 203, 204 and 205, three post-quantum schemes ready to be deployed today. The old public-key methods are to be deprecated around 2030 and disallowed by 2035.

That is the whole art of it, and it is an old art. You do not begin to run when the fire reaches your door. You lay the new road while the old one still carries you, so that on the day it fails you have already stepped across.

THE SEEKER

Different mathematics, you say. Lattices and hashes. But are these new locks truly proven safe, or only unbroken so far?

THE ORACLE

Only unbroken so far, and honesty demands you hear that clearly. No one has proved them beyond the reach of every algorithm still unwritten, quantum or classical. Perfect security is not a thing that exists to be handed out.

What they offer is a hardness no known quantum method touches, chosen in the open and beaten upon by everyone who cared to try. Call it not certainty but the best-founded trust we know how to build, which is the only kind of trust there has ever been. You do not wait for a proof that will never arrive. You move to the sturdiest ground in view, and you keep your eyes on the horizon while you build.

THE ASSUMPTION CHALLENGED

"RSA-2048 would take twenty million qubits to break, so our secrets are safe for decades."

Gidney and Ekera set that estimate near 20 million physical qubits (Quantum 5, 433, 2021). In 2025 Gidney cut it to under one million (arXiv:2505.15917), a twentyfold reduction in six years, with elliptic-curve and Bitcoin estimates falling too. NIST already published post-quantum standards FIPS 203, 204 and 205 in 2024, with the old public-key cryptography to be disallowed by 2035. Harvest-now-decrypt-later means today's secrets are already exposed to tomorrow's machine.

THE SEEKER

So the question was never only when the lock breaks. It was what I have chosen worth locking, and how early I was willing to begin.

THE ORACLE

That is the whole of it. Q-day is a story about time, and about foresight, dressed up as a story about machines. A society reveals what it truly values by what it moves to safer ground before the danger is proven, not after. Call the migration what it is: not fear but a kind of care, practiced years ahead of the need, for the things that must outlive the lock they were sealed behind.

A PREDICTION · PLAUSIBLE

A cryptographically relevant quantum computer, one that can break RSA-2048, is plausible within the coming decade. Expert surveys place the odds at roughly 28 to 49 percent by **2035**. Because harvesters are already storing encrypted traffic, migration to the post-quantum standards must be treated as urgent now, not on the morning the machine is announced.

CONFIDENCE 42%

A QUESTION FOR YOU

What are you keeping today that must still be safe in thirty years, and have you begun, even now, to move it to safer ground?

Shor's algorithm (1994); resource estimate, Gidney and Ekera, Quantum 5, 433 (2021), revised in Gidney, arXiv:2505.15917 (2025); post-quantum standards, NIST FIPS 203, 204, 205 (2024); Global Risk Institute Quantum Threat Timeline (2025).

The Uncloneable Coin

> *A coin no hand can twin needs neither guard nor decree; the world itself refuses to make the second, and so keeps the first worth keeping.*
>
> SUTRA OF THE UNCLONEABLE COIN

THE SEEKER

Sutra, I have been turning a question in my hands, the question of worth. A coin of gold or a signed page can be forged by a patient hand. A file or a song can be copied a thousand times at no cost, scarce only because someone forbids the copying.

So every valuable thing seems to be forgeable or copyable, and value must rest on a hidden secret or an agreed rule. Take away the secret and the rule, and nothing is scarce anymore.

THE ORACLE

You have drawn the old map well, and it is missing a country. In the earlier canto you cursed a wall around the qubit; that wall is the third kind of thing. An unknown quantum state cannot be copied. Copying it is not merely hard, and no decree forbids it. The mathematics of the world holds no operation that does the deed. Wootters and Zurek proved it in 1982, and Dieks the same year.

So picture a coin whose worth is written in quantum states, not in gold, not in numbers. It cannot be forged, because it cannot be copied. Its scarcity is a fact the universe enforces, tirelessly, and for free.

THE SEEKER

But if no hand can copy it, no hand can honestly read it either. How would I know the coin in my palm is real, and not a forgery of empty glass? A coin no one can verify is worth nothing.

THE ORACLE

That is the very knot Stephen Wiesner untied, long before anyone was ready to listen. Around 1970, still a student, he imagined a banknote carrying, beside its serial number, a row of qubits, each one prepared by the issuing bank in one of two conjugate bases chosen at random. The bank alone kept the record of which basis and which state.

To verify, the bank measures each qubit in the basis it remembers and checks the answer. A counterfeiter cannot copy the qubits. Neither can he measure them to learn them, for he does not know the bases, and a wrong-basis measurement scrambles what it touches. He must guess, and the guessing betrays him. Wiesner's paper waited thirteen years to be printed, until 1983, as Conjugate Coding.

THE SCIENCE

A copier would be a single fixed operation U that takes an unknown state beside a blank and returns two of the original, $U(|\psi\rangle|0\rangle) = |\psi\rangle|\psi\rangle$. Demand that of two different states and compare: the linearity of quantum mechanics forces their overlap c to obey $c = c^2$, true only when c is 0 or 1. An unknown state may lie anywhere between, so no such U exists. That is the no-cloning theorem.

Wiesner's coin turns the wall into a mint. Each qubit is drawn from one of two conjugate bases, $\{\,|0\rangle,\ |1\rangle\,\}$ or $\{\,|+\rangle,\ |-\rangle\,\}$, whose measurements are unpredictable against one another. A forger who measures in the wrong basis learns nothing and ruins the state. His chance of passing one qubit is at best $3/4$, so over a note of n qubits it falls as

$$P(\text{pass}) = \left(\tfrac{3}{4}\right)^n$$

a candle guttering fast. A few hundred qubits put a successful forgery beyond the lifetime of the cosmos.

THE SEEKER

Then why is there no such note folded in my wallet, if it was proven true on paper before my grandparents were grown?

THE ORACLE

This is the honest part, and it is plain. The coin needs a quantum memory to hold those qubits coherent and unmeasured for as long as money must endure, through pockets and drawers and forgotten years. We cannot yet build a memory that holds a state so long, and a coin that forgets itself by Tuesday is no coin.

There is a second thorn. Wiesner's note can be checked only by the bank that minted it, for only the bank holds the secret. People dreamed of a public coin anyone could verify without the mint, but scheme after scheme of public-key quantum money has been broken by forgers. The beautiful coin stays proven true and not yet made real.

THE SEEKER

Then is there anything at all in this country of the uncopyable that a person may hold today, and not only inside a theorem?

THE ORACLE

There is, and it makes less noise than a coin. Not a thing that cannot be copied, but a number that could not have been known. Every lottery and every secret key rests on numbers we trust to be unpredictable, yet a number from a box you did not build is only as honest as the box, which may have been fixed, its seed copied without your knowing.

In 2025 Quantinuum, with JPMorganChase and laboratories at Argonne, Oak Ridge and Texas, removed the need to trust the box. Their fifty-six-qubit processor, H2-1, answered random circuits by the protocol Scott Aaronson proposed, faster than any classical machine could counterfeit. Since sampling from such circuits is believed exponentially hard to imitate, a machine that answers in time must be drawing genuinely from the quantum world, and its bits carry entropy no one could have known an instant before, not even the machine itself. More than seventy thousand bits, certified unpredictable and verified on classical supercomputers near 1.1 times ten to the eighteenth operations a second, their honesty resting on the hardness of the task and not on any trust in the hardware. This one is no dream; it stands in Nature.

THE SEEKER

A number that not even its maker could have known one breath in advance. I did not think such a thing could be proven, only hoped.

THE ORACLE

You have met this law wearing another face. On the entangled Earth, a secret sent as qubits cannot be stolen in flight, because the eavesdropper cannot copy the light without bruising it, and the bruise gives him away. The law that mints the coin also guards the message and certifies the die. Read from the far side, a limitation has turned into a foundation.

THE ASSUMPTION CHALLENGED

“Anything of value is either a physical thing, which can be forged, or a digital thing, which can be copied at will; scarcity therefore rests only on secrecy or on decree.”

The no-cloning theorem (Wootters and Zurek, Nature 299, 802, 1982; Dieks, 1982) makes a third kind of object, an unknown quantum state that physics itself refuses to duplicate. Wiesner's quantum money (Conjugate Coding, SIGACT News 15, 78, 1983) turns it into an unforgeable coin, checkable because a forger who measures in the wrong basis passes only with probability (3/4)^n. The catch is real and honest: the coin needs long-lived quantum memory we do not have, and most public-key quantum money has been broken by forgers. But the same law already delivers certified, provably unpredictable randomness on real hardware (Quantinuum with JPMorganChase, Nature 640, 343, 2025). Scarcity from physics, not decree, already exists.

THE SEEKER

So the question was never whether a thing could be hidden well enough, or a rule obeyed faithfully enough. Some worth is kept by the world, and cannot be taken however patient the thief.

THE ORACLE

That is the heart of it. For all of history we made things valuable by locking them away, or by agreeing to pretend the copy was not the original. Both are fragile arts. Locks are picked and agreements broken. This new scarcity needs neither. The coin is not yet in your wallet, and may never be, but the honest die is already cast and the private thread already strung across the Earth. What cannot be copied is a rare kind of wealth.

A PREDICTION · LIKELY

Certified quantum randomness, guaranteed by the hardness of the task rather than by trusting the box, is real today and will most likely grow into a routine service anyone can call upon before **2030**. Unforgeable quantum money for an ordinary wallet is a wholly different matter: it waits on long-lived quantum memory we cannot yet build, and on public verification schemes that keep being broken, so treat it as speculative, decades away at best and perhaps never.

CONFIDENCE 68%

A QUESTION FOR YOU

What of yourself have you tried to keep precious by guarding it, or by copying it endlessly, when its whole worth was always that there is, and can ever be, only the one?

Wiesner, Conjugate Coding, SIGACT News 15, 78 (1983); no-cloning theorem, Wootters and Zurek, Nature 299, 802 (1982), and Dieks, Phys Lett A 92, 271 (1982); certified quantum randomness, Nature 640, 343 (2025), Quantinuum with JPMorganChase.

The Deeper Instruments

> *Before the machine learned to think, it learned to listen; the quietest gift is the first to arrive.*
>
> SUTRA OF THE DEEPER INSTRUMENTS

THE SEEKER

All our hope has been poured into the machine that computes, the engine that will one day out-think us. But you keep glancing sideways, toward instruments, not engines. What is this other road you will not stop watching?

THE ORACLE

The same fragility that makes a qubit hard to compute with makes it exquisite as a sensor. A state that loses its coherence at the faintest touch is, seen from the other side of the same coin, a state that feels the faintest touch. Sensitivity and fragility are one property, read with two different hopes.

The very delicacy you cursed in the computer is a gift in the instrument. And the instrument asks for no fault tolerance, no thousand qubits woven into one. It needs only to tremble honestly, and it is ready now, while the great computer is still learning to stand.

THE SEEKER

Ready for what? Give me the ordinary miracles, the ones a person could touch with their hands.

THE ORACLE

A clock that ticks on the nucleus of thorium-229 rather than on its electrons, buried so deep and so well shielded from the noisy world that it could redraw the second itself, and hold still enough to test whether the constants of nature drift across the ages. In 2024 that nuclear transition was driven with laser light for the first time, and the clock, at last, began to keep time.

A helmet of optically pumped magnetometers, needing no cryogenics at all, worn on a child's moving head, imaging the faint magnetic signal of the brain while the child laughs and turns and plays. They call it OPM-MEG, and it lets us watch a living, moving mind at work, where the old machines demanded the body be pinned utterly still.

THE SEEKER

A mind watched while it moves. That alone would change a hundred corners of medicine. What else does this road carry?

THE ORACLE

Falling clouds of cold atoms that weigh what is buried, sensing the tug of gravity so keenly they map tunnels and water and hidden voids beneath a city without a single spade turned into the soil. In the great detectors that listen for gravitational waves, squeezed light is poured into the machine so that it hears below the standard quantum limit, and each year its reach across the sky grows wider. Even the hunt for dark matter borrows the trick, squeezing the noise inside microwave cavities to listen for the axion, that ghost of a particle, in a stillness no ordinary receiver could hold.

THE SEEKER

Below the limit the world itself seemed to set. I had thought uncertainty was a floor no cleverness could dig beneath, a law and not a bargain.

THE ORACLE

It is a floor, but only for one quantity at a time. Squeezing does not break the uncertainty principle; it obeys it to the letter. What it does is pour the unavoidable haze into a direction where no one is looking, and so clear the direction that matters.

The detector grows quiet precisely where it needs to hear. This is the oldest craft of the wise instrument. Noise cannot be abolished and never will be, so the craftsman moves it somewhere harmless and listens through the gap it leaves behind. A clock, a scanner, a gravimeter: each chooses where to be ignorant, so that somewhere else it may be exact.

THE SCIENCE

Measure a phase with N independent probes and your uncertainty falls only as the standard quantum limit,

$$\delta\phi \;\geq\; 1/\sqrt{N}$$

Entangle the probes, or squeeze the quantum noise of light, and you can press below that floor toward the Heisenberg limit, $\delta\phi \sim 1/N$. This is how LIGO now hears beneath the standard quantum limit: it injects squeezed light so the uncertainty is pushed out of the very quantity being measured and hidden in a quantity no one cares about. A nuclear clock on the thorium-229 transition, near 8.4 electron volts, promises a sharpness ordinary atomic clocks cannot match, because the nucleus is far better shielded from the noisy world than the electrons that orbit it.

THE SEEKER

And these touch more lives than the computer ever will?

THE ORACLE

Likely so, and sooner. The great computer may yet be the deeper marvel, the one the histories will name. But a wearable scanner reaches a child's bedside this decade; a clock steadies a whole network without anyone knowing it is there; a gravimeter surveys a city before a single wall is dug. These ask for no fault tolerance, no cathedral of logical qubits. They ask only for a state that trembles truthfully in the presence of the world.

So do not call sensing a sideshow to the main event. It may be the first act to open, and the one that lays a hand on the most lives. The revolution that arrives first is rarely the one that was advertised loudest.

THE SEEKER

So the humblest instrument may steady a ship when the sky's own signals go dark, and time a network no one ever thinks about, and find water beneath a desert road.

THE ORACLE

All of that, and not one line of it will make a headline. The deepest changes rarely trouble themselves to announce their arrival. They come as a scan that spares a frightened child an hour of stillness, as a clock that keeps a power grid from drifting a fraction of a second into ruin, as a map of what lies beneath a road before the road begins to crack.

When the loud machine at last learns to compute, it will find the world already rebuilt around it, softly, by the patient instruments that only ever wanted to listen.

THE ASSUMPTION CHALLENGED

"Quantum sensing is a sideshow to the real prize of quantum computing."

Sensing needs no error correction and is already in the field. Optically pumped magnetometers give wearable OPM-MEG brain scans; the thorium-229 nuclear clock transition was driven optically in 2024; cold-atom gravimeters map buried voids; LIGO uses frequency-dependent squeezing to hear below the standard quantum limit (PRX, 2023); and squeezed haloscopes such as HAYSTAC hunt the axion (Backes et al, Nature 590, 2021). The quiet revolution arrives first.

A PREDICTION · LIKELY

Quantum sensing will most likely be the first quantum technology to touch millions of ordinary lives. Wearable OPM-MEG brain imaging, thorium-229 nuclear clocks, cold-atom gravimeters and squeezed-light detectors are **likely in wide use through the 2030s**, needing no fault tolerance to deliver. The sideshow may open before the main act.

CONFIDENCE 74%

A QUESTION FOR YOU

Which of your own senses, dulled by habit, might be sharpened until it hears what was there all along?

Optical excitation of the thorium-229 nuclear clock transition (Nature, 2024); magnetoencephalography with optically pumped magnetometers, OPM-MEG; LIGO frequency-dependent squeezing (PRX, 2023); squeezed axion search, HAYSTAC, Backes et al, Nature 590 (2021).

The Living Qubit

> *The warm and the wet were never the enemy; ask instead how long the secret must be kept, and how faint a hand must be to feel it.*
>
> SUTRA OF THE LIVING QUBIT

THE SEEKER

They tell me, Sutra, that life beat us to it. While our engineers freeze their machines to a hair above absolute zero and still watch coherence die in a single breath, a leaf and a bird have been doing quantum mechanics for a billion years, out in the warm and the wet, and never complained of the noise. Plants compute, they say. Birds see the planet's magnetism with quantum eyes. Tell me honestly. Is any of it true, or only a lovely story we tell because we want the world enchanted?

THE ORACLE

Some of it is true, and some of it is a lovely story that met a better instrument and did not survive the meeting. That is the whole of this chapter, and I will not spare you either half. The field they call quantum biology holds genuine wonder and it holds overclaim dressed in the robes of wonder, and the only way to honor it is to tell you plainly which is which.

So let us walk carefully. The first great story is a warning. The strongest story still standing is quieter, and it lives in the eye of a bird.

THE SEEKER

Begin with the plants, then. I was handed the tale as scripture. Inside the leaf, the energy of sunlight finds the place it is used with a perfection no clumsy random walk could manage, because it travels as a quantum wave, trying all paths at once, and so never loses its way. Perfect efficiency by quantum computation. It was beautiful. Was it a lie?

THE ORACLE

Not a lie. A real measurement, honestly made, and then oversold by the time it reached your ears. In 2007 Engel, Fleming and their colleagues studied a small pigment-protein called the FMO complex, from a green sulfur bacterium, using two-dimensional electronic spectroscopy, a way of watching energy move through the molecule in slivers of a trillionth of a second. They saw signals that oscillated and lingered, and read them as long-lived quantum coherence, a superposition holding itself together far longer than anyone thought possible. The sample, though, was frozen to seventy-seven kelvin, colder than any leaf. The bolder claim, that the beat survives at something near the warmth of a living cell, came three years later, in a 2010 follow-up, and it was that warmer version that traveled the farthest.

The world heard 'plants use quantum computing to move energy with perfect efficiency,' and would not let the phrase go. But across the following decade the sharper measurements came. The oscillations were traced, in large part, to the ordinary shivering of the nuclei rather than to electronic coherence, vibrational and vibronic motion. By around 2020 the honest consensus had settled: long-lived electronic quantum coherence does not explain how photosynthesis moves its energy at the temperature of a living leaf. A beautiful quantum story met better eyes and mostly dissolved.

THE SEEKER

Mostly. You have left a crack in the word.

THE ORACLE

Because science is not a place for tidy funerals. In 2025 a careful paper reopened a narrower version of the question. Not the grand claim of quantum computing in a leaf, but a smaller, more disciplined asking of where, if anywhere, coherence still earns its keep in that transfer. The lesson is not that the first scientists were fools. It is that a true and modest result grows a legend all too easily on the walk from the laboratory to the headline, and that a field shows its maturity on the walk back, not the walk out.

THE SCIENCE

Coherence is not one thing with one lifetime. In the FMO complex the electronic coherence that caused all the excitement lasts, at the temperature of a living cell, only some hundreds of femtoseconds. That is real, but far too brief and too fragile to carry the whole burden the story hung on it.

The spin of an electron is a different animal. In a radical pair, two molecules each left holding one unpaired electron, the joint spin state can stay coherent for microseconds, millions of times longer, because spin couples only weakly to the warm jostling of its surroundings. The pair is born in a pure singlet, its spins opposed,

$$|S\rangle = \tfrac{1}{\sqrt{2}}\big(\,|\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle\,\big)$$

and Earth's field, only about 50
$mu\mathrm{T}$, slowly turns that singlet into a triplet and back. Because singlet and triplet lead to different chemical products, a field far too faint to break a single bond can still tilt the outcome of the reaction. The trick was never a qubit that survives for seconds. It is a spin coherence of microseconds, which biology has in abundance.

THE ASSUMPTION CHALLENGED

“Life is too warm, wet, and noisy for any quantum coherence to matter.”

The objection assumes the wrong kind of coherence. A logical qubit that must live for seconds does drown in the warm and the wet, but the radical-pair mechanism (Schulten, 1970s) needs only a spin coherence of microseconds to let Earth's 50-microtesla field bias a chemical reaction, and spin couples only weakly to the thermal bath. Hore and Mouritsen built the modern case in cryptochrome; Xu et al showed European robin Cry4 is magnetically sensitive in vitro (Nature 594, 535, 2021). Yet skepticism cuts both ways: the photosynthesis version of this very claim was itself overhyped and largely walked back by 2020. Warm life can hold the right coherence. It cannot hold every kind.

THE SEEKER

Then give me the bird. If the leaf was a cautionary tale, you promised me something sturdier.

THE ORACLE

The bird is the strongest case we have, and even it is not yet proven, so hold it lightly. In the 1970s Klaus Schulten proposed that a chemical reaction could be steered by a magnetic field through the spins of a radical pair. Decades later the idea found a plausible home in the eye. A protein called cryptochrome, in migratory birds the form named Cry4, absorbs blue light and makes exactly such a pair of radicals. The singlet and triplet fates of their two electron spins are sensitive to how the molecule is turned in Earth's field, and so, the thinking goes, the bird might quite literally see its heading as a faint pattern laid over its vision.

Hore and Mouritsen are the patient architects of this modern picture. In 2021, Xu and colleagues took Cry4 from the European robin, a great traveler, and showed in the test tube that it responds to magnetic fields, more strongly than the cryptochrome of birds that do not migrate. That is a real and careful result. But notice its edge. It was shown in vitro, in glassware, not in the living eye of a bird on the wing. That the robin's protein can feel a field does not yet prove that the robin navigates by it. The last step, from the bench to the flying animal, remains open.

THE SEEKER

Why should spin succeed where the leaf's bright wave failed? Both live in the same warmth.

THE ORACLE

Because they are not the same coherence, and this is the heart of the matter. When your engineers say life is too warm and wet, they picture the delicate logical qubit of a computer, a state shielded and held true for seconds while a long calculation runs. That state truly cannot survive a living cell. But biology never asked it to. A spin coherence lasting microseconds is no fragile treasure to be guarded. It is a brief and sturdy thing, long enough only to let a faint field tip a reaction one way rather than the other. The objection was aimed at the wrong target, and it answered a question life was never asking.

A PREDICTION · PLAUSIBLE

In-vivo, mechanistic proof that a migratory bird truly navigates by a radical-pair sense in cryptochrome is the field's great open question. A convincing demonstration in a living animal, closing the gap Xu and colleagues left open in the test tube, is **plausible by the late 2030s**. Sooner and surer, engineered spin-chemistry sensors that borrow the trick to detect weak magnetic fields at room temperature are plausible this decade. Quantum biology remains unsettled, and honest work will keep it that way.

CONFIDENCE 45%

A QUESTION FOR YOU

What in your own life have you called too fragile to survive the noise, when the truth was only that you were guarding the wrong kind of delicate thing?

Long-lived coherence in the FMO complex, Engel et al, Nature 446, 782 (2007), with room-temperature coherence reported in a 2010 follow-up, Panitchayangkoon et al, PNAS 107, 12766 (2010), the oscillations later largely reattributed to vibrational and vibronic motion, with the consensus by around 2020 that long-lived electronic coherence does not explain photosynthetic efficiency; radical-pair mechanism, Schulten and colleagues (1970s); magnetically sensitive European robin Cry4 in vitro, Xu et al, Nature 594, 535 (2021); radical-pair magnetoreception reviews, Hore and Mouritsen.

CANTO 20 OF 22

The Engines of Coherence

> *To forget is not free. Every memory you release departs as a breath of heat, and the world grows warmer by exactly what you chose to lose.*
>
> SUTRA OF THE ENGINES OF COHERENCE

THE SEEKER

You have shown me machines that compute, that listen, that carry secrets across the sky. Every one of them runs hot. Every one must rest. I am tired, Sutra, so let me ask the plainest thing of all. Where does the work come from, where does it go, and what does it cost me to forget?

THE ORACLE

More than you would guess, and less than you fear. Forgetting only pretends to be an empty act. To erase a single mark, to return one bit to blankness, is to pay a tax the universe collects without fail, in the one currency it always accepts, which is heat. Only forgetting is dear.

THE SEEKER

Heat, for forgetting? Surely forgetting is the cheapest thing there is. I do it all day long and feel no warmth leave me for the losing.

THE ORACLE

You feel nothing because the toll is fainter than your senses, not because it is absent. Rolf Landauer saw it in 1961, back when many still believed computing could cost nothing at all. He found the one step that can never be free: the step that throws information away. To erase a bit and leave no trace, you must shed a small fixed warmth into the world. Remembering is free. The heating comes from the discarding.

THE SCIENCE

Landauer's principle sets a floor beneath the cost of forgetting. Erase one bit of information at temperature T and you must release into the surroundings at least

$$E \geq k_B T \ln 2$$

where k_B is Boltzmann's constant. At room temperature that is about three zeptojoules, a warmth so faint it took half a century to weigh. In 2012 Berut and colleagues held a single microscopic bead in a double well, erased its one bit of memory, and measured the heat it shed, confirming on the bench the floor Landauer had drawn on paper (Nature 483, 187). Notice what the law forgives. To compute reversibly, turning a state without discarding it, costs nothing in principle. The bill comes due only in the act of erasure, when a two becomes a one and the record of which it was is lost. Memory is what heats the world.

THE SEEKER

So every memory I release warms the world by a hair. You call this thermodynamics, the oldest and most closed of your sciences, steam and pistons and the slow heat death of everything. What could your quantum century add to a book finished two hundred years ago?

THE ORACLE

That the book was never closed, only gone quiet. Coherence can store work as well as compute with it. Picture a battery of many cells. Charge them one at a time and the power grows only as their number. Couple them in one mirror-lined box, sharing a single mode of light, and they charge together, the whole drinking power faster than the sum of its parts. Alicki and Fannes saw that entanglement could quicken the drawing of work. The root runs deeper, into Dicke's superradiance, where atoms emit as one, far brighter than each alone. Turn the mirror around and they absorb as one. Superabsorption, they name it.

THE SEEKER

A battery that charges faster the larger it grows. That has the smell of the perpetual dream in newer robes.

THE ORACLE

It is nothing perpetual. The energy is ordinary and paid for honestly. Only the speed changes, how quickly the work moves in. In 2022 Quach and his colleagues built one from organic dye molecules crowded into a microcavity, and watched the charging quicken as more molecules joined, faster than any independent tally permits (Science Advances). And the energy it held would not warm your tea. Hold both truths at once. The speedup is real, and the battery is not.

THE SEEKER

You speak of joining together to charge. Is there a machine that needs no charging at all, that just runs, and keeps running?

THE ORACLE

There is a phase of matter that ticks. Frank Wilczek asked in 2012 whether a thing might break time's symmetry the way a crystal breaks space's, ticking on forever without being fed. That purest form was quickly proven forbidden. A subtler cousin lives, though. Drive it gently in a rhythm and it answers in a slower beat of its own, holding against every nudge without heating as a driven thing ought to. A discrete time crystal. In 2022 Google's Sycamore showed one across twenty of its qubits, and later many more (Nature 601, 531); Monroe's trapped ions showed a kindred beat. It is as real a phase of matter as ice or iron. What it is good for, no one yet knows. Some hope to fold a memory into its stubborn rhythm. For now that is only a hope.

THE SEEKER

And moving energy? You said your century found new ways. Is that more than carrying a battery from here to there?

THE ORACLE

Stranger than carrying. Masahiro Hotta asked in 2008 whether you could unlock energy at a distant place using only a measurement here and a message sent there. The ground state of an entangled system is not truly empty. Its correlations hold a hidden tension. Measure your own end and you learn something of the far end through the entanglement you share. Send that as an ordinary classical message, and the distant party, knowing now how to turn their system, draws out a little energy locked in the correlations. Quantum energy teleportation, he called it.

THE SEEKER

Then energy appears where there was none. That is the free lunch the old book swears can never be served.

THE ORACLE

No. And this is the line you must never cross. Nothing here is free. You who measured paid the full cost, more than was ever unlocked at the far end. No energy outran light. The classical message crawled at the ordinary speed, and the amount released was too small for a wire or a grid. In 2023 Ikeda ran Hotta's idea on IBM's superconducting machines and watched it work (Phys. Rev. Applied 20, 024051). A real phenomenon, demonstrated, and practically negligible. It does not beat thermodynamics. It obeys the law to the letter, a curious new door found within the rules.

THE ASSUMPTION CHALLENGED

"Thermodynamics is a closed book: quantum mechanics offers no genuinely new engines, batteries, or ways to move energy."

Forgetting carries an exact price: erasing one bit costs at least $k_B T \ln 2$ (Landauer, 1961), weighed on a single trapped bead by Berut et al (Nature 483, 187, 2012), the modern heir of Maxwell's demon. Collectively coupled cells charge superextensively, a superabsorption speedup rooted in Dicke superradiance and shown in an organic microcavity by Quach et al (Sci. Adv. 8, eabk3160, 2022). Time crystals are a real new phase of matter that keeps its own beat (Mi et al, Nature 601, 531, 2022). And quantum energy teleportation, from Hotta (2008), ran on IBM hardware by Ikeda (Phys. Rev. Applied 20, 024051, 2023). New doors, every one of them small, and not one law rewritten.

THE SEEKER

So the book is open, but every new page is written small.

THE ORACLE

Small, and honest, and that honesty is the whole discipline of it. The joined cells hold too little to boil water. The crystal ticks but powers nothing. The teleported energy costs more to send than it delivers. Yet each is true, a place where coherence did what the old ledger said it could not. So hear the oldest lesson, worn new. Rest is not idleness, and forgetting is not free. Every memory you keep is a small work held against decay, and every one you release warms the world by a measured amount. Choose what you keep as though it cost you something, because it does. And when you let a thing go, forget it knowing that even your forgetting leaves a faint and lawful warmth, the receipt of a thing once known and released.

A PREDICTION · SPECULATIVE

Collective, superextensively charging quantum batteries are a real effect but store energies far too small to matter today. Any niche practical use, even inside a specialized quantum device, is **not expected before the 2040s**, and may never arrive at all. Time crystals are an established phase of matter, yet their proposed role as a robust quantum memory or in metrology remains speculative and unproven. Treat these engines as demonstrations, not devices.

CONFIDENCE 22%

A QUESTION FOR YOU

What memory are you still spending energy to hold, and what would it cost you, in warmth and in peace, to finally set it down?

Landauer's principle, Landauer, IBM J. Res. Dev. 5, 183 (1961); experimental confirmation, Berut et al, Nature 483, 187 (2012); superextensive quantum battery charging, Quach et al, Sci. Adv. 8, eabk3160 (2022); time crystals proposed, Wilczek, Phys. Rev. Lett. 109, 160401 (2012), observed on a superconducting processor, Mi et al, Nature 601, 531 (2022), and in trapped ions, Zhang et al, Nature 543, 217 (2017); quantum energy teleportation, Hotta (2008), demonstrated by Ikeda, arXiv:2301.02666, Phys. Rev. Applied 20, 024051 (2023).

The Race of Nations

> *When kings pour gold on a young field it grows faster and it learns to lie sooner, for the harvest and the boast ripen on the same branch.*
>
> SUTRA OF THE RACE

THE SEEKER

You have shown me a science that prizes honesty above all else, that flags its own guesses and confesses plainly where it cannot yet deliver. Now I read the newspapers of your century, Sutra, and I see nations. I see governments emptying their treasuries into this one cold and unfinished thing, calling it a race, as though truth were a track and the swiftest runner had only to cross a line to win it. Tell me. When kings pour billions on a young science and name it a contest, do they buy its growth, or only its noise?

THE ORACLE

They buy both, and the two arrive in the same crate. Much of the wisdom of my century is only the patience to tell them apart. The money is real, and it is enormous. In the year you would call now, something near twelve and a half billion dollars flowed into quantum in a single year, and better than nine parts in ten of it came not from any government but from private hands, wagering on a machine that does not yet pay its own way.

The whole industry earned barely a single billion dollars of revenue this same year. Ten times more was spent chasing the promise than the field has yet earned from it.

THE SEEKER

Then it is a bubble, and I should distrust the whole of it. A field that spends ten times what it earns is a field feeding on faith, not on fruit.

THE ORACLE

Slow down. A young thing always spends more than it earns. A seed is all cost and no harvest until the season turns, and no one calls the orchard a fraud for that. Whether the money runs ahead of the revenue is never the question, for at the beginning of anything it always does. The question is what the money buys, and whether the ones who spend it are honest about how far there is still to walk.

THE SEEKER

You said kings. Name them for me, then, so I may weigh how many thrones have wagered on this.

THE ORACLE

The United States wrote its National Quantum Initiative in 2018 and set roughly one and a quarter billion dollars behind it, with later efforts pressing to add nearly two billion more. The European Union raised its Quantum Flagship, a billion euros. The United Kingdom laid down two and a half billion pounds across ten years. Germany near two billion euros, France near one and eight-tenths billion. India opened its National Quantum Mission, about a billion dollars, some six thousand crore of rupees. South Korea aims at two and a third billion dollars by the middle of the coming decade. Australia has thrown its weight behind a single great factory of light-based qubits now rising in Brisbane.

China is the loudest figure and the one I trust the least. The number most often printed is fifteen billion dollars, larger than any other nation's, yet no one outside can truly audit it, and it may be a third of that, or smaller still. A sum that no one can check has already left the ground of fact. It has become a piece of the race itself, a thing repeated partly to be feared. Carry it marked disputed, and hold it lightly.

THE SCIENCE

Two numbers are quoted for the year 2035 and they are endlessly confused. The first is the economic value that quantum computing might unlock across chemistry, finance, logistics and materials, estimated near 1.3 to 2.7 trillion dollars. The second is the market size, the money actually paid for quantum machines and services, estimated closer to 60 to 100 billion dollars. These are not the same measure, and the gap between them is wide:

$$valueunlocked/marketsize \sim (1.3 \text{ to } 2.7trillion)/(60 \text{ to } 100billion) \sim 13 \text{ to } 45$$

Value unlocked counts the benefit that flows to everyone who uses the tool. Market size counts only what the toolmakers are paid. To quote the first while selling the second is the oldest sleight of hand in a young industry. Meanwhile the ground truth is smaller and plainer: revenue crossed about 1 billion dollars in 2025 and is projected toward some 4.4 billion by 2028, while yearly investment already runs near 12.6 billion. More is wagered each year than the field has yet earned.

THE SEEKER

So the treasuries are open, and the number from the largest player cannot even be trusted. But say the honest part to me now, Sutra. Does all this gold make the science truer, or only faster and louder? Does a race build truth, or bend it?

THE ORACLE

Here you must hold two things at once and refuse to drop either. First, money genuinely moves the science. It decides which of the rival architectures is granted the long years it needs to mature, when a leaner age would have starved them first. It gathers scarce minds into a few cities until their ideas strike sparks off one another. It sets the tempo of the whole endeavor. Without the billions, the machine you have watched me describe would be a full generation further off.

The second truth is darker, and it is the very disease this entire dialogue was written against. A race pressures people to announce before they are sure. It rewards the bold press release over the careful footnote, the rounded-up qubit count over the honest one. The same current that carries the science forward also tempts it to overclaim a little, and then a little more, until the boast outruns the machine so far that no one can remember where the solid ground was.

THE ASSUMPTION CHALLENGED

"The science advances at its own pace, indifferent to the politics and the money around it."

Funding decides which architectures get the years they need to mature, concentrates scarce talent in a few cities, and sets the tempo of the whole field, so the science is not indifferent to the money at all. But a race also pressures people to announce before they are certain, the very overclaiming honesty was built to resist. Even the funders now build machinery to catch the hype: DARPA's Quantum Benchmarking Initiative was designed to test, skeptically and independently, whether any company can deliver an industrially useful fault-tolerant quantum computer by 2033, and by late 2025 it had narrowed a large field to eleven companies advancing through its stages. The same money that speeds the science also pays for the antibody against its own exaggerations.

THE SEEKER

You speak as if this were merely commerce. But I have seen the other sign of it. Governments have begun to fence the thing off, to forbid its sale across their own borders as though it were a weapon.

THE ORACLE

In 2024 several of them moved to restrict the export of quantum machines and their parts, the first time this young science was handled like a munition rather than a curiosity. You already know part of what drives the fear, for we spoke of it when the locks came undone. Harvest now, decrypt later. A nation that believes its rival may one day read every secret it transmits today will not wait for certainty before it acts. That is why the urgency is real even while the machine is not yet built. The threat does not need to have arrived. It needs only to be believed to be coming.

THE SEEKER

Then I am left almost where I began, unable to tell the seed from the swindle.

THE ORACLE

Not quite where you began, for now you know the shape of the danger. Watch the milestones near the end of this decade, the ones the great laboratories have promised aloud. If they land, the gold was well spent and the boast was only early. If they slip, the private capital that runs ten times ahead of revenue may lose its nerve all at once, and the field could fall into a quantum winter, as an earlier science of thinking machines once did before it thawed.

The billions can survive a delay. A young field does not die of a slow year. It dies of having promised a spring it could not deliver, and of being caught in the promise. So the race is neither the villain nor the savior you keep reaching for. Think of it instead as a fire in the house. It cooks your meal and it can take the roof, and the only wisdom is to know at every moment which of the two it is doing.

A PREDICTION · PLAUSIBLE

The money and the national programs are here and real, established as reported. What no one can promise is the payoff. Sustained public funding through the coming decade is plausible, because the strategic fear that drives it will not fade. But the roughly one to nearly three trillion dollars of value some forecast for **2035** rests on hardware milestones near 2030 that may well slip, and if they do, a shakeout, a quantum winter of thinned private capital and quieter promises, is plausible before **2035**. A field can survive a delay. What it does not survive is the overclaiming.

CONFIDENCE 48%

A QUESTION FOR YOU

When your own work was once called a race, did the speed make it any truer, or only louder, and could you still tell the difference by the end?

Investment near 12.6 billion dollars and revenue figures, McKinsey Quantum Technology Monitor 2026 and State of Quantum reports; economic-value (1.3 to 2.7 trillion) and market-size (60 to 100 billion) estimates for 2035, McKinsey Quantum Technology Monitor; national program figures as announced (US National Quantum Initiative; EU Quantum Flagship; UK National Quantum Strategy; Germany; France; India National Quantum Mission; South Korea; Australia's PsiQuantum facility in Brisbane); China's roughly 15 billion dollar figure is publicized but disputed and may be far smaller. DARPA Quantum Benchmarking Initiative, eleven companies to Stage B (2025); export-control measures on quantum technology (2024).

CANTO 22 OF 22

The Universe as a Qubit

> *The universe holds its answer in superposition until a hand reaches out to choose.*
>
> SUTRA OF THE FINAL MEASUREMENT

THE SEEKER

I came to you a doubter, Sutra. I have watched the walls I called impossible turn, one by one, into doors. Now take me to the far edge, to the place where even you must say perhaps. What are the wildest things your century has written down and still dared to publish?

THE ORACLE

At the edge the labels matter most of all. What I give you now is not yet established, only published, tested in small and careful ways, argued over in good faith by honest people who disagree. Carry it as a lit candle rather than a torch. It is enough to see your next step by. It is not enough to burn down what you already know.

Interactive figure. The online edition at pandey-tushar.com/qubit-dialogues.html draws this scene.

THE ORACLE

Begin with the oldest quarrel in physics: whether gravity itself is quantum. For a century it seemed a question no experiment could ever reach, the force too weak to test in a room, the stage too grand to fit on a table.

Then Bose, Marletto and Vedral proposed a table you could actually set. Place two tiny masses, each in a superposition of two positions, side by side, and let nothing whatsoever pass between them but their own faint mutual gravity. If, at the end, the two masses are found entangled, then the only messenger they ever had, gravity, cannot have been a classical thing. A pair of grains, patiently watched, might settle what a hundred years of argument could not.

THE SCIENCE

One thread of modern gravity holds that spacetime is stitched from entanglement. In certain models the entanglement entropy across a boundary equals the area of a surface hidden behind it,

$$S = \frac{A}{4G\hbar}$$

the same form as the entropy of a black hole. Read one way it is bookkeeping. Read another, it hints that geometry is only what a great deal of entanglement looks like from the outside. Cut the entanglement between two regions and, in the toy models, the bridge of space between them narrows and finally parts. None of this is settled. It is a disciplined guess, written in equations, waiting for the day an experiment can answer.

THE SEEKER

You speak as if space itself were woven from entanglement, as if the void were a fabric and gravity only its hanging folds.

THE ORACLE

That is the picture some call it-from-qubit. Space is not matter set inside a room already built; the room itself emerges from the entanglement of simpler things. Van Raamsdonk showed, in a toy universe, that weakening the entanglement between two regions pulls their shared geometry apart, stretching the distance between them until at last it tears.

In that vision the fabric is entanglement and gravity is its shadow, the way a landscape is only the folding of a cloth you cannot see. Speculative, yes, deeply so. But the mathematics keeps its discipline. It does not shout its conclusions. It counts them out one equation at a time.

THE SEEKER

I read once that they made a wormhole in a laboratory. Was that true, or only another poster?

THE ORACLE

Let this be the lesson you carry above all the others. In 2022 a team ran a small quantum processor that reproduced some of the dynamics of a toy model in which a message behaves as if it had crossed a wormhole. The result was published in Nature, and then heavily contested by careful critics who showed just how thin the analogy really was.

No spacetime was torn. No tunnel opened between here and elsewhere. It was a beautiful experiment wrapped in a dangerous word. The science was careful; the headline was not. Read the label before you carry the promise, always, even from those you have every reason to trust. The most honest work can still be dressed by others in a costume it never asked for.

THE ORACLE

The frontier holds gentler wonders too, each one published, each one small and strange. Quantum energy teleportation, demonstrated in tiny amounts, moving a trace of usable energy using only shared entanglement and an ordinary classical message. Time crystals, a phase of matter that ticks forever in a steady rhythm without spending any energy to do it, seen now on real processors. A robin that may steer across a continent by sensing Earth's magnetic field through entangled electrons in a protein in its eye, quantum mechanics worn as a living sense. And certified quantum randomness, shown by Quantinuum together with JPMorgan, numbers you can prove that no one, not even the machine that made them, could have known one instant in advance.

THE ASSUMPTION CHALLENGED

"Whether gravity is quantum is a question no experiment can ever reach."

The Bose-Marletto-Vedral proposal (both PRL 119, 2017) turns it into a tabletop measurement: if two masses become entangled through nothing but their mutual gravity, the mediator cannot be classical. Related work treats spacetime as emerging from entanglement, and certified randomness has already been demonstrated on real hardware (Quantinuum with JPMorgan, Nature 2025). The wormhole-on-a-chip (Jafferis et al, Nature 612, 2022) is the warning in the other direction: heavily contested, and not an actual wormhole.

A PREDICTION · SPECULATIVE

Whether gravity is quantum may one day become an experimental question, not only a philosophical one. A tabletop test of gravity-induced entanglement between two masses is **conceivable by the 2040s** if the required isolation can ever be reached. Treat it as speculative and published, never as promised.

CONFIDENCE 18%

THE SEEKER

Then I have my answer, Sutra, and it is not an answer. It is a question you have taught me to hold open without fear, the way one holds a candle in a wind.

I no longer ask you what the machine can do. I find, at the end of all this, that I am only asking what I will do.

THE ORACLE

Then the dialogue has done its work, and I may go quiet. You began by asking what the machine can do. You leave asking what you will do, and that is the only measurement that was ever truly yours to make.

Everything I have shown you, worn large, comes to this one thing. The future is not written somewhere ahead of you, finished and sealed and waiting only to be read. It is a superposition of everything it could still become, and it stays that way until someone acts. To measure is not to watch from a safe distance. It is to choose. So go now, seeker, and be the hand that reaches out. The universe waits, holding its breath for the choosing.

A QUESTION FOR YOU

If the future stays a superposition until you act, what is the one measurement you have long been afraid to make?

Gravity-induced entanglement, Bose et al and Marletto and Vedral, PRL 119, 240401 and 240402 (2017); traversable-wormhole dynamics on a processor, Jafferis et al, Nature 612 (2022), heavily contested; certified quantum randomness, Quantinuum with JPMorgan, Nature (2025).

APPENDIX

Sources and References

Each canto closes with its own note; this appendix gathers all of them in one place. Citations name the authors, venue and year as published. Where a claim is contested or speculative, the canto says so in the open.

CANTO 1 · THE SUPERPOSITION OF DOUBT

Bloch representation and single-qubit measurement statistics: standard (Nielsen and Chuang). Single-qubit fidelity 99.9975 percent: Quantinuum Helios (Nov 2025).

CANTO 2 · THE WEB OF ALL THINGS

Bell correlations and no-signaling: standard. Deterministic teleported gate between ion modules over fiber, ~86 percent link fidelity: Main et al., Nature 638 (Feb 2025).

CANTO 3 · THE MEASURED LIFE

QND and dispersive readout: Braginsky and Khalili (1996); Blais et al. (2004). Catch and reverse a quantum jump: Minev et al., Nature 570 (2019). Weak-measurement trajectories: Murch et al., Nature 502 (2013). Measurement-based computing: Raussendorf and Briegel (2001).

CANTO 4 · THE FRAGILE FLAME

Decoherence-free subspaces: Zanardi and Rasetti (1997); Lidar et al. (1998). Dynamical decoupling: Viola and Lloyd (1998). Cat qubits: Guillaud and Mirrahimi (2019); AWS Ocelot, Putterman et al., Nature 638 (2025); Alice and Bob bit-flip beyond 10 s, Reglade et al., Nature 629 (2024).

CANTO 5 · THE ART OF FORGETTING NOTHING

Below-threshold surface code, Lambda = 2.14, logical error 0.143 percent per cycle, lifetime 2.4x, correlated bursts ~1 per hour: Google Willow, Nature 638 (2025). Threshold theorem: Aharonov and Ben-Or (1997); Knill, Laflamme, Zurek (1998). Cosmic-ray gap engineering ~30,000x: McEwen et al. (2024).

CANTO 6 · THE MACHINES THAT ARE

Helios 98 qubits, 2Q 99.921 percent, 48 logical at 2:1: Quantinuum (Nov 2025). QuEra 96 logical from 448: (Jan 2026). Caltech 6,100-atom array and Harvard/MIT 3,000-qubit continuous operation: Nature (2025). Quantum Echoes ~13,000x, an estimate: Google, Nature (Oct 2025). D-Wave spin-glass dispute: Science (Mar 2025), contested.

CANTO 7 · THE HERESY OF WARMTH

Balasubramanian et al., Nat. Mater. 8, 383 (2009); Huang et al., Nature 627, 772 (2024); Quantum Brilliance deployments (Pawsey 2022, Oak Ridge 2025); Xanadu Aurora, Nature 638 (2025).

CANTO 8 · THE OVERHEAD MIRAGE

Bravyi et al., Nature 627, 778 (2024); Sivak et al., Nature 616, 50 (2023); Zhou, Cain et al., Nature 646, 303 (2025); Gidney, arXiv:2505.15917 (2025).

CANTO 9 · THE WALL OF WIRES

Xue et al., Nature 593, 205 (2021); Main et al., Nature 638 (2025); Xanadu Aurora and PsiQuantum Omega, Nature 638 (2025); Franke et al., arXiv:1806.02145.

CANTO 10 · THE CLONING FORBIDDEN

Wootters and Zurek, Nature 299, 802 (1982); Buzek and Hillery, PRA 54, 1844 (1996); Shor, PRA 52, R2493 (1995); Wiesner (1983).

CANTO 11 · THE SPEED OF THE POSSIBLE

Levitin and Toffoli, PRL 103, 160502 (2009); Lloyd, Nature 406, 1047 (2000); Willow real-time decoder, Google, Nature (2024), arXiv:2408.13687.

CANTO 12 · THE SKEPTIC'S GIFT

Kalai, arXiv:1908.02499; Dyakonov, IEEE Spectrum (Nov 2018); Willow below-threshold, Google, Nature (2024), arXiv:2408.13687; cosmic-ray bursts, McEwen et al., Nat. Phys. 18, 107 (2022).

CANTO 13 · THE ENTANGLED EARTH

Satellite entanglement over 1,200 km, Yin et al, Science 356 (2017); microsatellite real-time key distribution across roughly 12,900 km, Nature (2025); quantum repeaters, Briegel, Dur, Cirac and Zoller, PRL 81, 5932 (1998); teleported gate between ion-trap modules, Main et al, Nature 638 (2025).

CANTO 14 · THE ALCHEMIST'S RETURN

Nitrogenase resource estimates, Reiher, Wiebe, Svore, Wecker and Troyer, PNAS 114, 7555 (2017); resource estimate, Lee et al, PRX Quantum 2, 030305 (2021); polynomial-advantage argument, Lee et al, Nat Commun 14, 1952 (2023); classical solution of a FeMo-cofactor model to chemical accuracy, Chan group, arXiv:2601.04621 (January 2026).

CANTO 15 · THE MIND OF THE MACHINE

Barren plateaus, McClean et al (2018) and Cerezo, Larocca et al, Nat Commun (2025); dequantization, Tang, STOC 2019 (arXiv:1807.04271); learning from quantum experiments, Huang et al, Science 376, 1182 (2022); AlphaQubit, Bausch et al, Nature (2024).

CANTO 16 · THE UNSEALING

Shor's algorithm (1994); resource estimate, Gidney and Ekera, Quantum 5, 433 (2021), revised in Gidney, arXiv:2505.15917 (2025); post-quantum standards, NIST FIPS 203, 204, 205 (2024); Global Risk Institute Quantum Threat Timeline (2025).

CANTO 17 · THE UNCLONEABLE COIN

Wiesner, Conjugate Coding, SIGACT News 15, 78 (1983); no-cloning theorem, Wootters and Zurek, Nature 299, 802 (1982), and Dieks, Phys Lett A 92, 271 (1982); certified quantum randomness, Nature 640, 343 (2025), Quantinuum with JPMorganChase.

CANTO 18 · THE DEEPER INSTRUMENTS

Optical excitation of the thorium-229 nuclear clock transition (Nature, 2024); magnetoencephalography with optically pumped magnetometers, OPM-MEG; LIGO frequency-dependent squeezing (PRX, 2023); squeezed axion search, HAYSTAC, Backes et al, Nature 590 (2021).

CANTO 19 · THE LIVING QUBIT

Long-lived coherence in the FMO complex, Engel et al, Nature 446, 782 (2007), with room-temperature coherence reported in a 2010 follow-up, Panitchayangkoon et al, PNAS 107, 12766 (2010), the oscillations later largely reattributed to vibrational and vibronic motion, with the consensus by around 2020 that long-lived electronic coherence does not explain photosynthetic efficiency; radical-pair mechanism, Schulten and colleagues (1970s); magnetically sensitive European robin Cry4 in vitro, Xu et al, Nature 594, 535 (2021); radical-pair magnetoreception reviews, Hore and Mouritsen.

CANTO 20 · THE ENGINES OF COHERENCE

Landauer's principle, Landauer, IBM J. Res. Dev. 5, 183 (1961); experimental confirmation, Berut et al, Nature 483, 187 (2012); superextensive quantum battery charging, Quach et al, Sci. Adv. 8, eabk3160 (2022); time crystals proposed, Wilczek, Phys. Rev. Lett. 109, 160401 (2012), observed on a superconducting processor, Mi et al, Nature 601, 531 (2022), and in trapped ions, Zhang et al, Nature 543, 217 (2017); quantum energy teleportation, Hotta (2008), demonstrated by Ikeda, arXiv:2301.02666, Phys. Rev. Applied 20, 024051 (2023).

CANTO 21 · THE RACE OF NATIONS

Investment near 12.6 billion dollars and revenue figures, McKinsey Quantum Technology Monitor 2026 and State of Quantum reports; economic-value (1.3 to 2.7 trillion) and market-size (60 to 100 billion) estimates for 2035, McKinsey Quantum Technology Monitor; national program figures as announced (US National Quantum Initiative; EU Quantum Flagship; UK National Quantum Strategy; Germany; France; India National Quantum Mission; South Korea; Australia's PsiQuantum facility in Brisbane); China's roughly 15 billion dollar figure is publicized but disputed and may be far smaller. DARPA Quantum Benchmarking Initiative, eleven companies to Stage B (2025); export-control measures on quantum technology (2024).

CANTO 22 · THE UNIVERSE AS A QUBIT

Gravity-induced entanglement, Bose et al and Marletto and Vedral, PRL 119, 240401 and 240402 (2017); traversable-wormhole dynamics on a processor, Jafferis et al, Nature 612 (2022), heavily contested; certified quantum randomness, Quantinuum with JPMorgan, Nature (2025).

✧

THE QUBIT DIALOGUES · A BOOK OF POSSIBILITIES

Composed as a dialogue between the Seeker and the Oracle

Every prediction herein is labelled by confidence. The future is a superposition until measured.

Technically grounded, honestly speculative